CP violation in hadronic penguins at *BaBar*

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Seminar at Fermi National Accelerator Laboratory
January 27, 2009

Overview

- CP violation introduction.
- Measuring $\sin 2\beta$ in $b \to c\bar{c}s$ modes such as $B^0 \to J/\psi K_S^0$.
- Motivation for measuring $\sin 2\beta_{\text{eff}}$ in $b \to q\bar{q}s$ $(q = u, d, s)$ penguins.
  - $B^0 \to \eta' K^0, \phi K_S^0, \omega K_S^0, \pi^0 K_S^0$
- Previous results.
- PEP-II collider, $B\!A\!B\!A\!R$ detector, and dataset.
- $B^0 \to \eta' K^0$ analysis (part of my thesis).
- Recent results from other penguins.
- Discussion.

Symmetries

- Discrete transformations C, P, and T:

  - Parity $(P) : (t, \mathbf{x}) \to (t, -\mathbf{x})$.

  - Time-reversal $(T) : (t, \mathbf{x}) \to (-t, \mathbf{x})$.

  - Charge-conjugation (C) :
    particles $\to$ anti-particles

- Strong and electromagnetic forces conserve C, P, and T.

- In 1956, the weak force was observed to violate P; the $V - A$ form of the weak force manifestly violates C and P.

- It was thought that weak interactions conserved CP, until Cronin and Fitch observed $K^0_L \to \pi^+ \pi^-$ in 1964.

- In `90s, B-factories built to test CKM picture of CP violation in decays of B mesons.

CKM matrix and *CP* violation

- Consider the coupling of quarks to charged gauge bosons in the flavor (interaction) basis:

$$\mathcal{L}_W = g_W \left(\overline{u}^L \gamma^\mu W_\mu^+ d^L + \overline{d}^L \gamma^\mu W_\mu^- u^L \right)$$

- Transform to mass basis with $u^{L\prime} = U^u u^L, \quad d^{L\prime} = U^d d^L$:

$$\mathcal{L}'_W = g_W \left(\overline{u}^L \gamma^\mu W_\mu^+ V d^L + \overline{d}^L \gamma^\mu W_\mu^- V^* u^L \right)$$

where $V = (U^{u\dagger} U^d)$ is the CKM quark mixing matrix.

- CKM matrix is 3×3 unitary matrix characterized by three real parameters and one irreducible phase.

- Because of CKM phase, $V \neq V^*$ and $\mathcal{L}'_W$ is not invariant under CP.

CKM basics

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- By convention, V_{CKM} takes down-type quarks from flavor to mass basis.

- In Wolfenstein parameterization (to order λ^3):

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where λ is the sine of the Cabibbo angle ($\lambda = V_{us} \simeq 0.22$) and A, ρ, and η are real and of order 1.
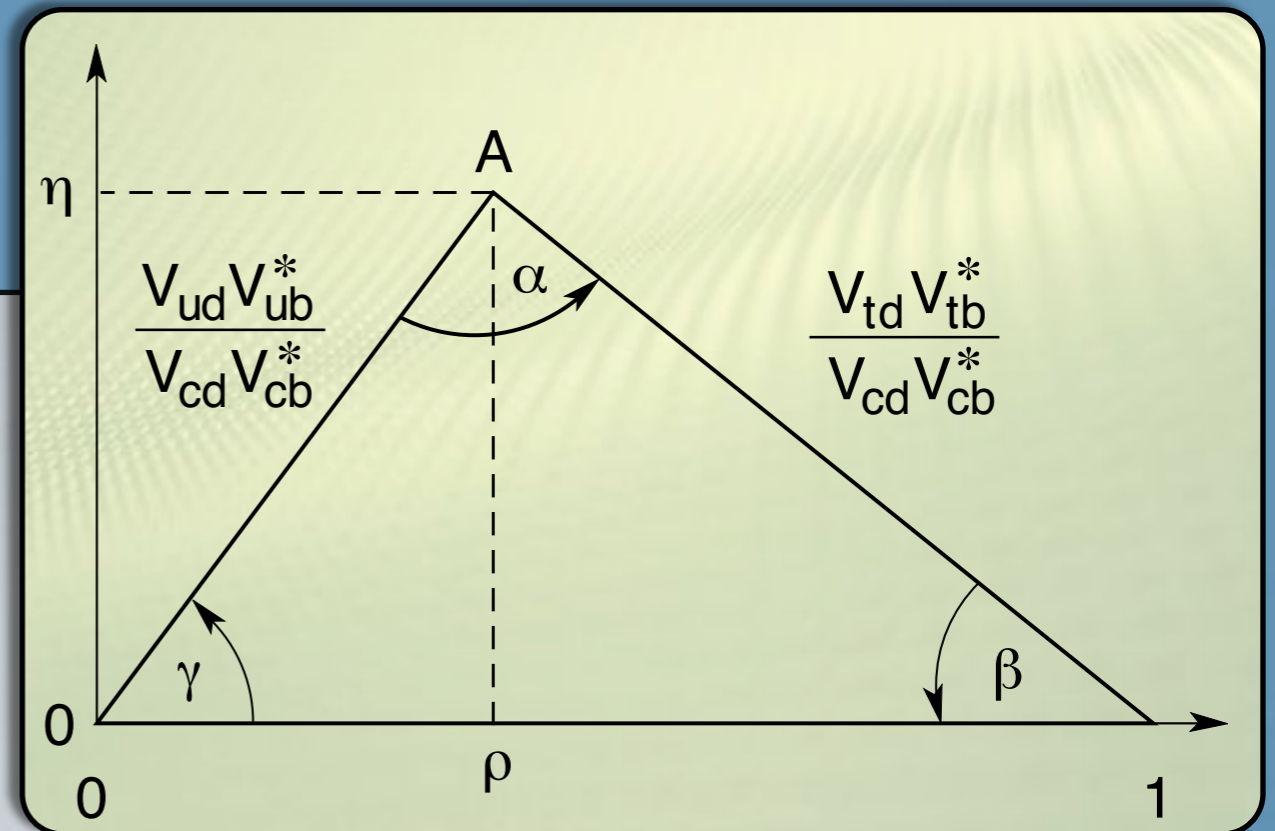
- $\eta \neq 0$ implies CP violation.

Unitarity triangle

- Unitarity of V_{CKM} yields

$$\sum_{i=u,c,t} V_{ij}V_{ik}^* = 0.$$

$(j = d,s,b; \ k = d,s,b; \ \text{and} \ j \neq k)$

- Useful for the B system, this equation

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

describes a triangle in complex plane of roughly equal sides.

- The apex is at $\rho + i\eta$, so that non-zero area implies CP-violation.

- The angles are defined

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \ \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \ \text{and} \ \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right].$$

Overconstraining the triangle

- Measure the sides and angles of the unitary triangle in diverse processes.

- Agreement confirms the CKM picture.

- Disagreement indicates new physics.
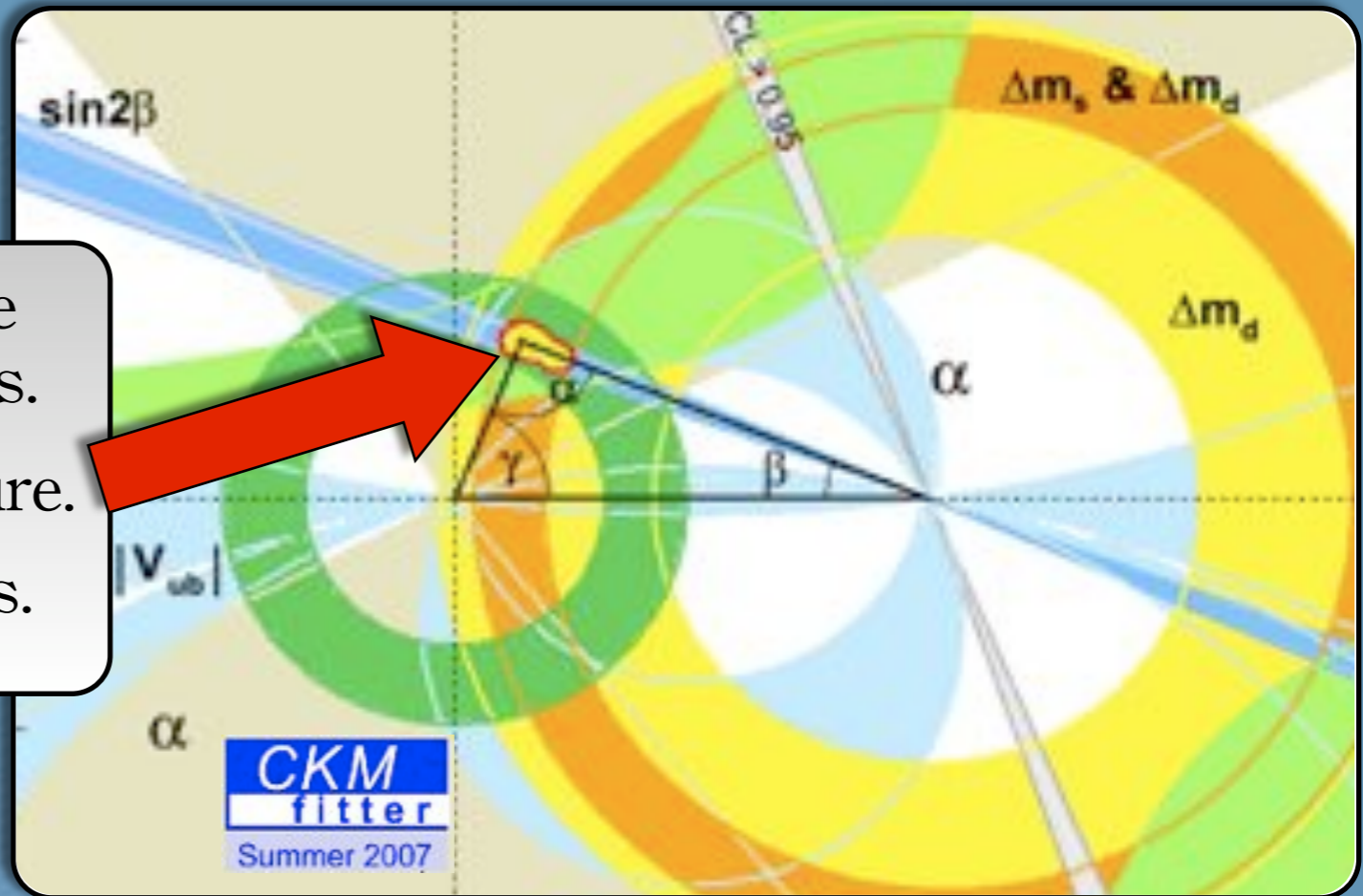
Wassily Kandinsky
Composition VIII, 1923

$B\overline{B}$ Time Evolution

- At *BABAR*, pairs of B mesons are created in entangled states in $\Upsilon(4S)$ decays.

- Mass and flavor eigenstates differ:

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$
$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

- Neutral B`s, created in flavor states, mix via second-order weak process (box diagram).

$$\Delta m_B \equiv m_H - m_L$$
$$\Delta\Gamma_B \equiv \Gamma_H - \Gamma_L$$
$$M \equiv (m_H + m_L)/2$$
$$\Gamma \simeq \Gamma_H \simeq \Gamma_L$$

- A B^0 meson at $t = 0$ can be written at t:

$$|B^0_{\text{phys}}(t)\rangle = e^{-iMt}e^{-\Gamma t/2}\left[\cos\left(\tfrac{1}{2}\Delta m_B t\right)|B^0\rangle + i\tfrac{q}{p}\sin\left(\tfrac{1}{2}\Delta m_B t\right)|\overline{B}^0\rangle\right]$$

- No *CP* violation in mixing, q/p is pure phase.

- Note $\Delta\Gamma_B \ll \Delta m_B$, $\Delta\Gamma_K \simeq 2\Delta m_K$, $\Delta m_B = 100 \cdot \Delta m_K$.
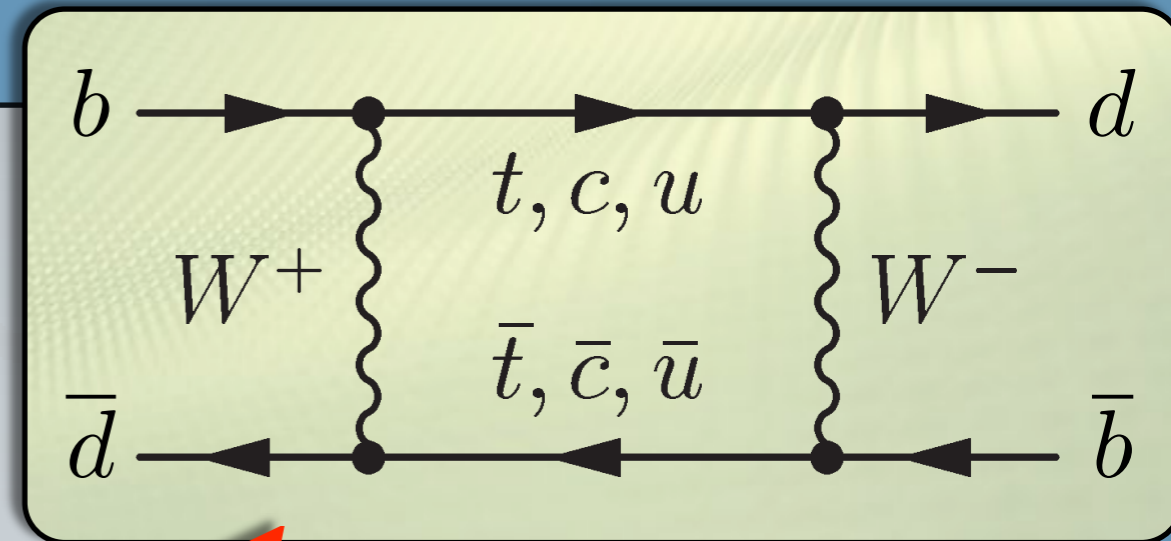
Mixing-induced CP violation

- Decay to CP eigenstate f_{CP} $(\psi K_S^0, \eta' K^0)$ accessible from B^0 and $\overline{B}^0$ involves interference between amplitudes for mixing (q/p) and decay $(A_{f_{CP}}, \overline{A}_{f_{CP}})$.

- The observable time-dependent decay rate asymmetry:

$$A_{CP}(t) = \frac{\Gamma(B^0_{\text{phys}}(t) \to f_{CP}) - \Gamma(\overline{B}^0_{\text{phys}}(t) \to f_{CP})}{\Gamma(B^0_{\text{phys}}(t) \to f_{CP}) + \Gamma(\overline{B}^0_{\text{phys}}(t) \to f_{CP})}$$

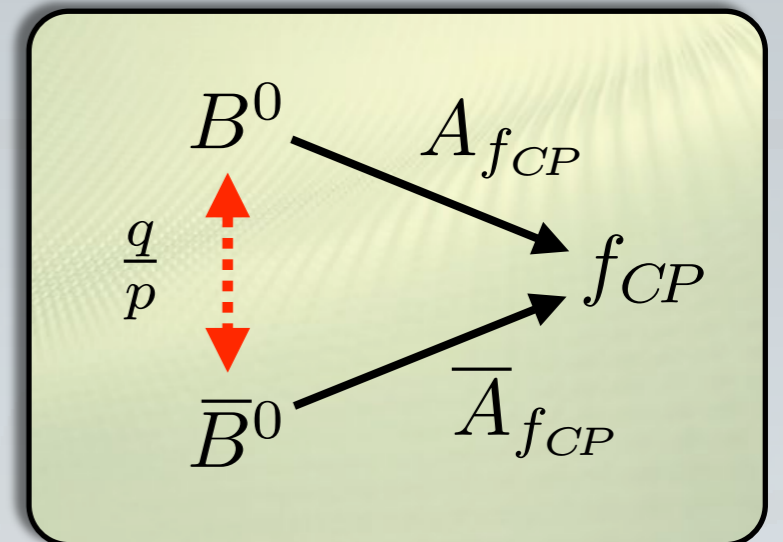- Decay rates Γ (now called $f_\pm$) are

$$f_\pm(t) = \frac{e^{-t/\tau}}{4\tau} \left[1 \pm S_{f_{CP}} \sin(\Delta m_B t) \mp C_{f_{CP}} \cos(\Delta m_B t) \right]$$

- Mean B^0 lifetime is τ, the CP-violation parameters $S_{f_{CP}}$ and $C_{f_{CP}}$ are

$$S_{f_{CP}} \equiv \frac{2 \operatorname{Im}\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}, \qquad C_{f_{CP}} \equiv \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}, \qquad \lambda_{f_{CP}} \equiv \eta_{f_{CP}} \frac{q}{p} \frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}$$

- For CP conservation, $A_{CP} = S_{f_{CP}} = C_{f_{CP}} = 0$.

Experimental Aside...

- So far, $A_{CP}(t)$ and $f_{\pm}(t)$ are written in terms of the flavor at creation and the time of decay of a B meson (B_{CP}).

- We can`t measure these, BUT ...

- Recall coherent B meson pairs (B_{CP} and B_{tag}).

- We can determine:
    - flavor at decay (tag) of the other B meson (B_{tag}),
    - difference between proper times of decays of B_{CP} and B_{tag}.

- We can write:

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left[1 \pm S_{f_{CP}} \sin(\Delta m_B \Delta t) \mp C_{f_{CP}} \cos(\Delta m_B \Delta t)\right]$$
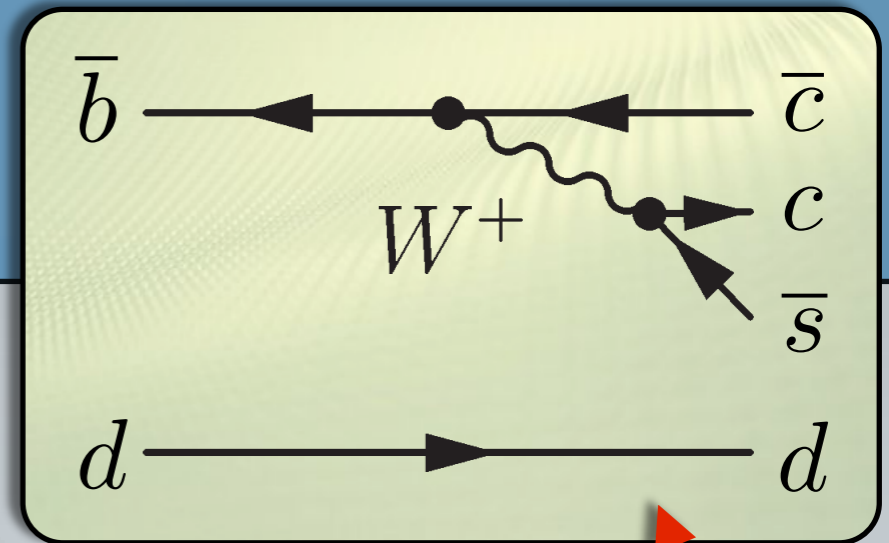
where $\Delta t \equiv t_{CP} - t_{\text{tag}}$ and the upper (lower) sign denotes a decay accompanied by a B^0 ($\overline{B}^0$) tag.

- We use $f_{\pm}(\Delta t)$ in the ML fit to extract $S_{f_{CP}}$ and $C_{f_{CP}}$ from the data.

$\sin 2\beta$ from $b \to c\bar{c}s$

- Examine $\lambda_{f_{CP}}$ in ``golden mode`` $B^0 \to \psi K_S^0$:

$$\lambda_{f_{CP}} \equiv \eta_{f_{CP}} \frac{q}{p} \frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}$$

$\eta_{f_{CP}}$	CP eigenvalue of f_{CP}.
$q/p \simeq V_{tb}^* V_{tb}/V_{tb} V_{td}^*$	From B mixing, independent of f_{CP}.
$A_{\psi K_S^0} \propto V_{cb} V_{cs}^*$	Single amplitude for $B^0 \to J/\psi K_S^0$.
$V_{cs} V_{cd}^*/V_{cs}^* V_{cd}$	From K mixing in the final state.

- In SM, we expect (almost exactly):

$$\lambda_{\psi K_S^0} = - \left(\frac{V_{td} V_{tb}^*}{V_{cb}^* V_{cd}} \right) \left(\frac{V_{cb} V_{cd}^*}{V_{td}^* V_{tb}} \right)$$

- And $S_{\psi K_S^0} = \text{Im}\lambda_{\psi K_S^0} = \sin 2\beta$ $\qquad$ $C_{\psi K_S^0} = \frac{1-|\lambda_{\psi K_S^0}|^2}{1+|\lambda_{\psi K_S^0}|^2} = 0$

- No CP violation in decay because $\left| \frac{\overline{A}_{\psi K_S^0}}{A_{\psi K_S^0}} \right| = 1$; only ~1 amplitude contributes.

$\sin 2\beta_{\text{eff}}$ from $b \to q\bar{q}s$ penguin decays

- $b \to q\bar{q}s$ decays occur via loop processes in SM.

- $b \to s$ penguin diagrams carry same phase as $b \to c$ tree diagram.

- Penguins also sensitive to $\sin 2\beta$.

- S/C can be non-zero when two amplitudes with differing weak and strong phases contribute to the process.

- Color-suppressed tree and CKM-suppressed penguin amplitudes pollute the picture.

- $|\overline{A}_{\eta'K^0}|/|A_{\eta'K^0}| - 1 = \mathcal{O}(\lambda^2)$, so we expect:
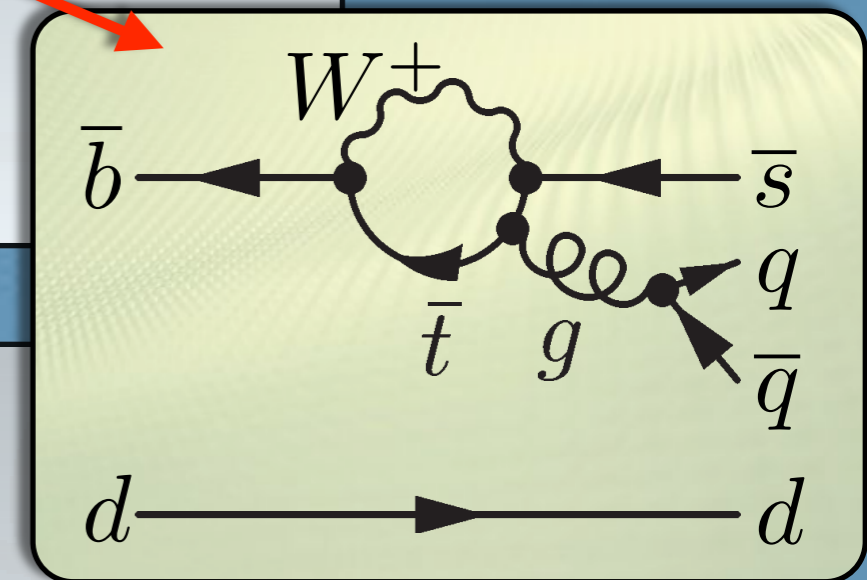
$$S_{\eta'K^0} = \sin 2\beta_{\text{eff}} \simeq \sin 2\beta$$
$$C_{\eta'K^0} \simeq 0$$

ΔS and new physics

- $\sin 2\beta_{\text{eff}}$ measured in $b \to q\bar{q}s$ penguin decays is sensitive to heavy, non-SM particles in loop.

- Deviations of ΔS ($\equiv \sin 2\beta_{\text{eff}} - \sin 2\beta$) from zero indicate new physics.

- However, even in SM, channel dependent effects cause $\Delta S \neq 0$.

- There are predictions for ΔS from
  - QCD factorization.
  - Soft collinear effective theory.
  - Flavor SU(3) symmetry.

- $\eta' K^0$ and ϕK_S^0 are theoretically cleanest modes with $\Delta S \sim 0.03$.

Theory Predictions for ΔS
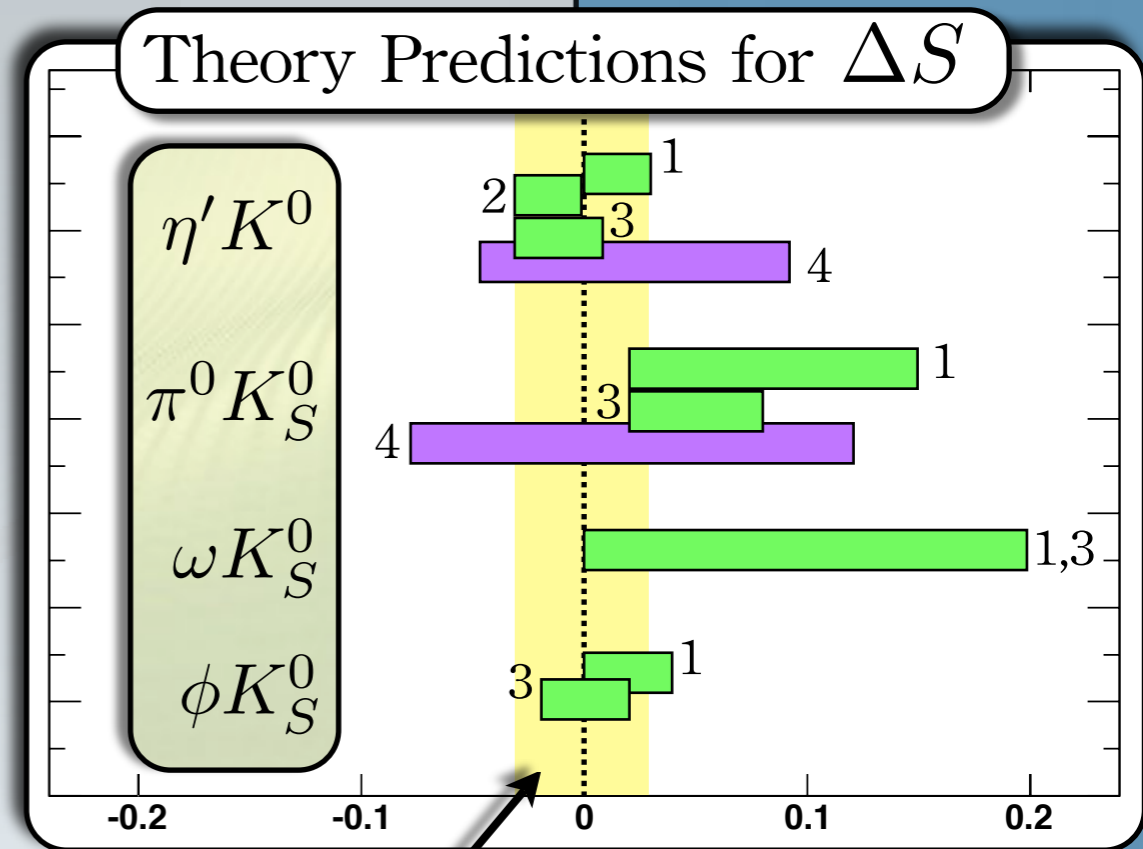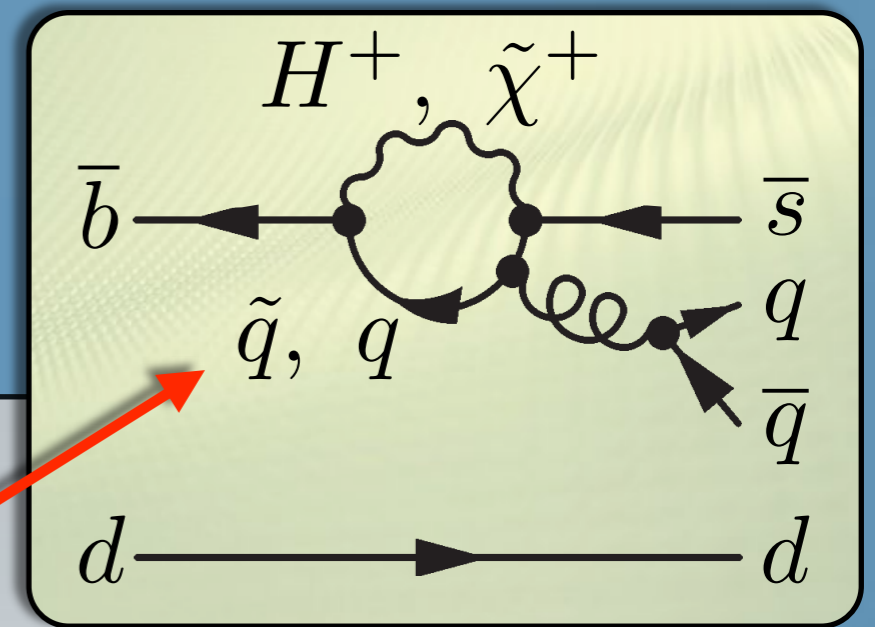
Yellow band is uncertainty on $\sin 2\beta$ (± 0.03).

[1]QCDF Beneke, PLB620, 143 (2005)
[2]SCET/QCDF Williamson, Zupan, PRD74, 014003 (2006)
[3]QCDF Cheng, Chua, Soni, PRD72, 014006 (2005)
[4]SU(3) Gronau, Rosner, Zupan, PRD74, 093003 (2006)

Previous Results

First observation of CP violation in charmless B decays.

	$BABAR$ [1]	Belle [2]
$S_{\eta' K^0}$	$0.58 \pm 0.10 \pm 0.03$	$0.64 \pm 0.10 \pm 0.04$
$C_{\eta' K^0}$	$-0.16 \pm 0.07 \pm 0.03$	$-0.01 \pm 0.07 \pm 0.05$
$-\eta_{\eta' K_S^0} S_{\eta' K_S^0}$	0.62 ± 0.11	0.64 ± 0.11
$C_{\eta' K_S^0}$	-0.18 ± 0.07	0.03 ± 0.07
$-\eta_{\eta' K_L^0} S_{\eta' K_L^0}$	0.32 ± 0.28	0.46 ± 0.24
$C_{\eta' K_L^0}$	-0.16 ± 0.07	-0.09 ± 0.16

World averages (Summer `07) for $b \to s$ penguins.

- In 2005, naive average of $b \to s$ penguins differed from $b \to c\bar{c}s$ was 3.7σ.

- At last publication, discrepancy was 1.6σ (neglecting $f_0 K_S^0$).

Recent results presented today for these modes.
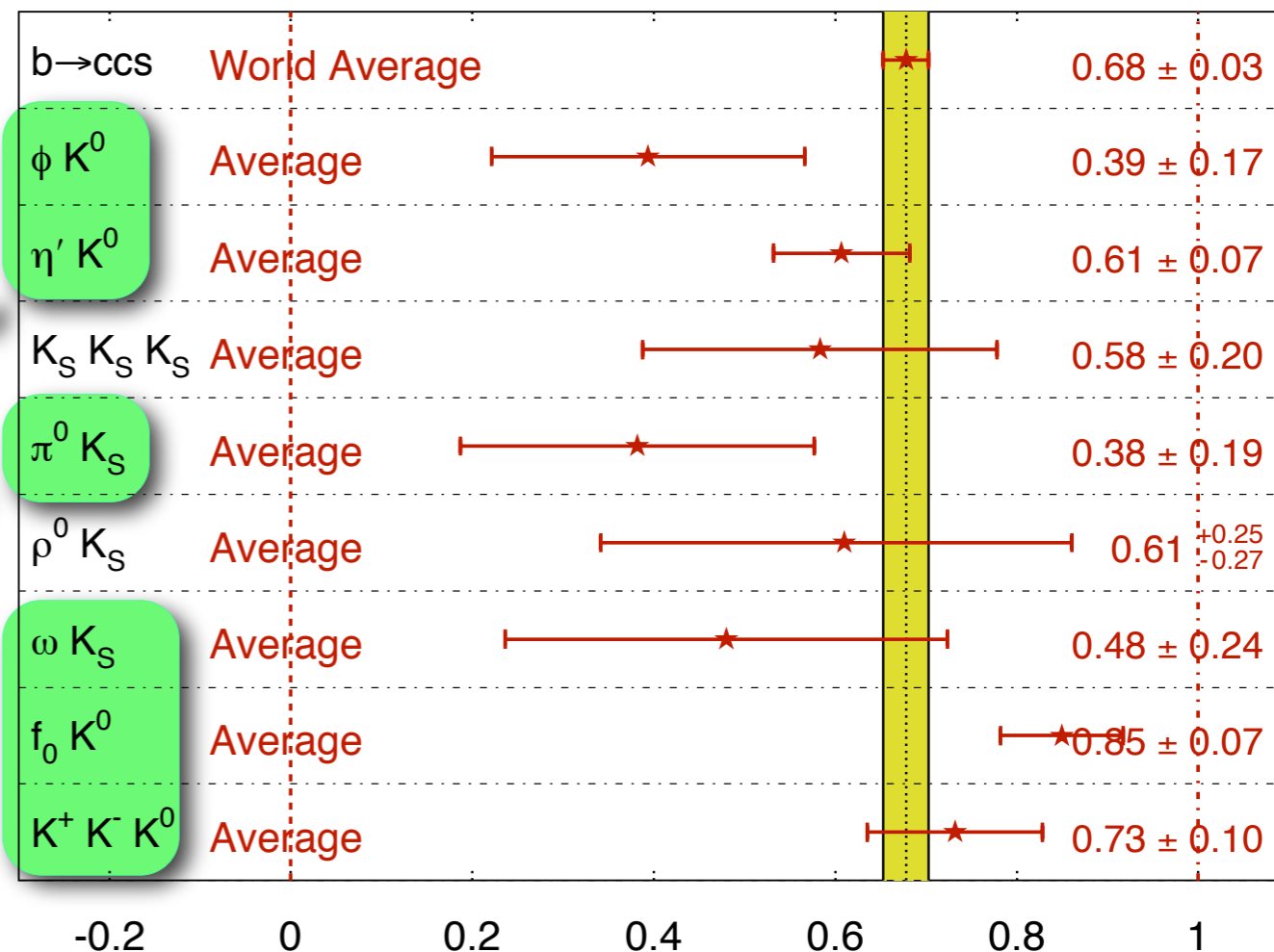
[1] Babar Collab., PRL 98, 031801 (2007).
[2] Belle Collab., PRL 98 031802 (2007).

$$\sin 2\beta_{\text{eff}}$$

HFAG
LP 2007
PRELIMINARY

b→ccs	World Average	0.68 ± 0.03
ϕK^0	Average	0.39 ± 0.17
$\eta' K^0$	Average	0.61 ± 0.07
$K_S K_S K_S$	Average	0.58 ± 0.20
$\pi^0 K_S$	Average	0.38 ± 0.19
$\rho^0 K_S$	Average	$0.61 ^{+0.25}_{-0.27}$
ωK_S	Average	0.48 ± 0.24
$f_0 K^0$	Average	0.85 ± 0.07
$K^+ K^- K^0$	Average	0.73 ± 0.10

PEP-II

- Asymmetric-energy e^+e^- collider. (9 GeV e^-, 3.1 GeV e^+)

- Center of mass (CM) is boosted in lab ($\beta\gamma = 0.56$).

- Separation of $B\overline{B}$ decay vertices: $20\mu\text{m} \rightarrow 200\mu\text{m}$.

- $\sqrt{s} \equiv E_{\text{CM}} = 10.58$ GeV (Mass of $\Upsilon(4S)$)

- $\mathcal{B}(\Upsilon(4S) \rightarrow B\overline{B}) \simeq 100\%$

- Max luminosity four times that of design: $1.2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$

SLAC

Aerial photo mosaic courtesy of Steve Williams. (www.pam-rc.org)

Linac

End Station A: partons via DIS

SPEAR: J/ψ, τ lepton

SLD: Precision Z studies

BABAR

15

$\mathcal{B}A\mathcal{B}AR$ Detector

Silicon Vertex Tracker

5-layer SVT measures track impact parameters.

Drift Chamber (DCH)

- 40-layer, small-cell.
- Measures p_T.
- PID for tracks with $p_T < 0.7$ GeV from dE/dx.

Magnet

1.5 Tesla, superconducting magnet.

e^+

e^-

DIRC

144 silica bars measure angle of Cherenkov cone, primary PID for tracks with $p_T > 0.7$ GeV.
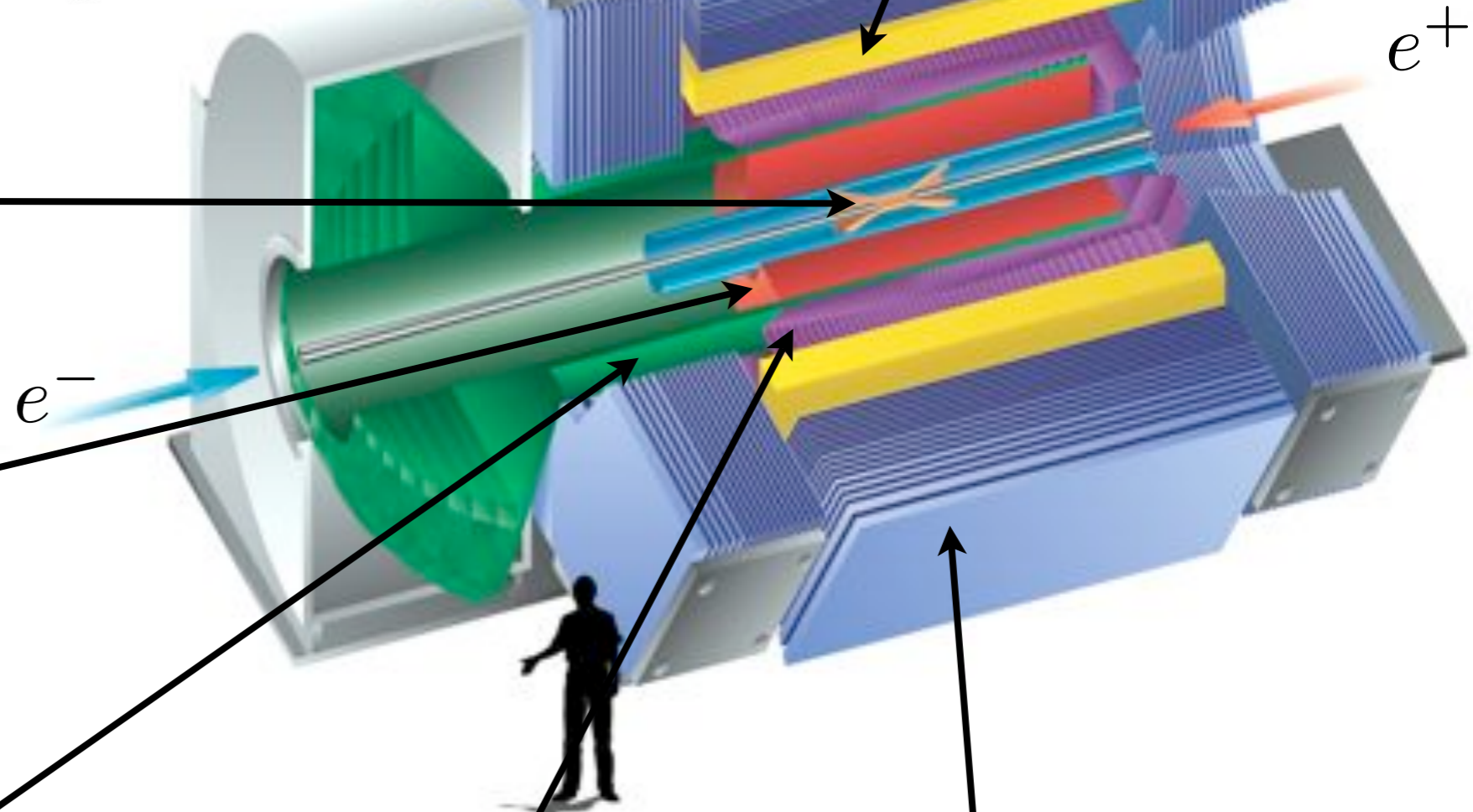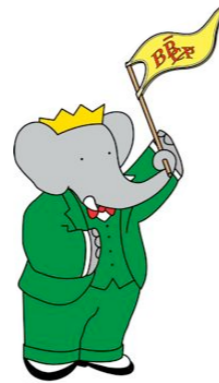
ElectroMagnetic Calorimeter (EMC)

56 rings of CsI crystals. Detects energy from photons, electrons, and K_L^0.

Instrumented Flux Return (IFR)

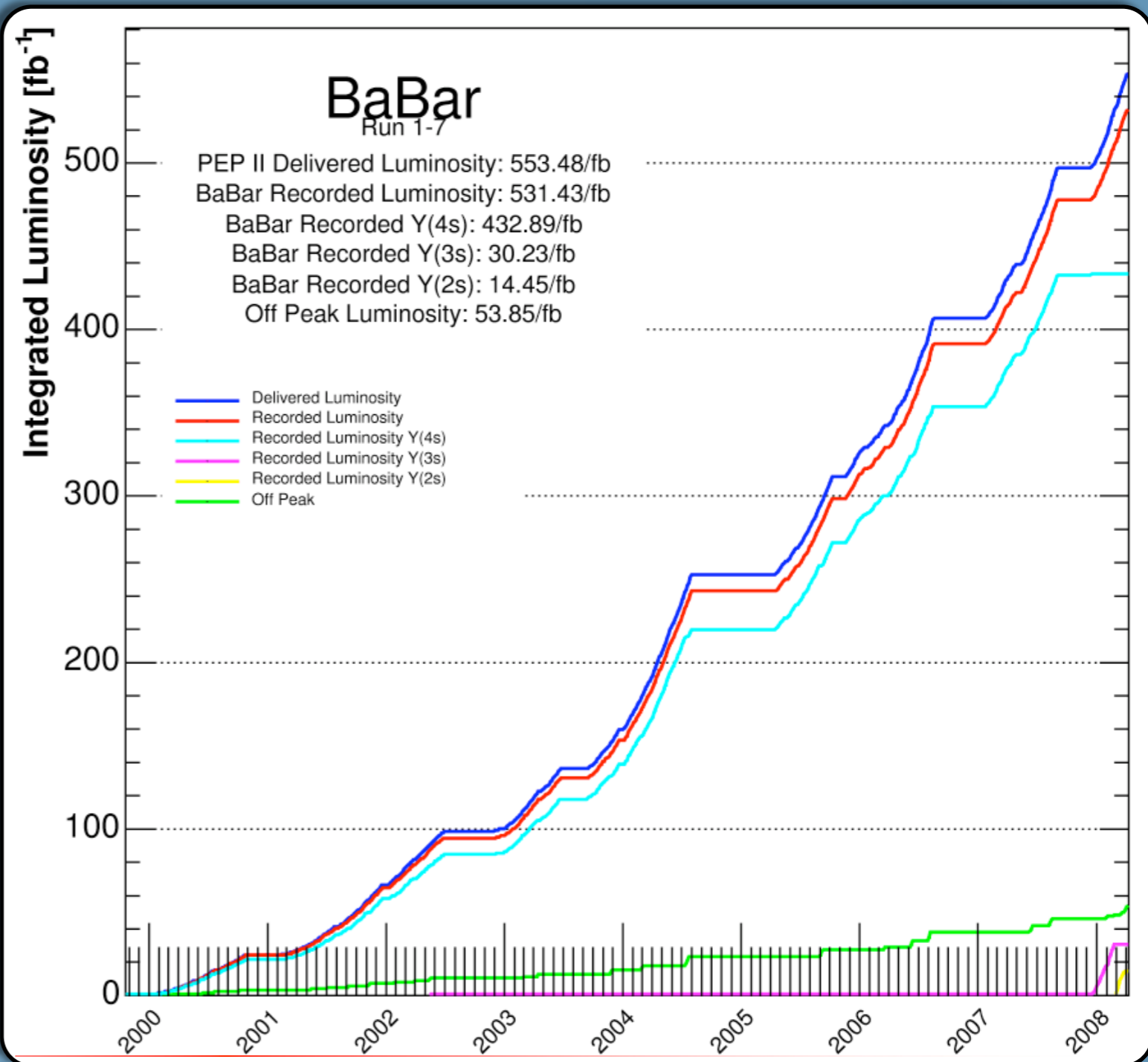Resistive plate chambers and limited streamer tubes detect muons and K_L^0.

Data & Monte Carlo

- Data collected 1999-2008.

- 426 fb^{-1} on-resonance. ($\sqrt{s} = 10.58$ GeV)

- 54 fb^{-1} off-resonance.

- $B\bar{B}$ production cross-section of ~1.1 nb yields 467 million $B\bar{B}$ pairs.

Large samples of GEANT4 MC

- Exclusive samples for signals and backgrounds from B decays (0.2 -1.0 million events each).
- Inclusive sample of generic $B\bar{B}$ decays (1.3 billion events).

BaBar
Run 1-7

PEP II Delivered Luminosity: 553.48/fb
BaBar Recorded Luminosity: 531.43/fb
BaBar Recorded Y(4s): 432.89/fb
BaBar Recorded Y(3s): 30.23/fb
BaBar Recorded Y(2s): 14.45/fb
Off Peak Luminosity: 53.85/fb

Delivered Luminosity
Recorded Luminosity
Recorded Luminosity Y(4s)
Recorded Luminosity Y(3s)
Recorded Luminosity Y(2s)
Off Peak

$B^0 \to \eta' K^0$ Analysis

- Measure S and C using seven sub-decay modes.

- Crosscheck with $\eta'_{\rho\gamma} K^+$ and $\eta'_{\eta\pi\pi} K^+$.

Decay Name Key

$\eta'_{\eta\pi\pi} : \eta' \to \eta\pi^+\pi^-, \eta \to \gamma\gamma$

$\eta'_{\rho\gamma} : \eta' \to \rho\gamma$

$\eta'_{5\pi} : \eta' \to \eta\pi^+\pi^-, \eta \to \pi^+\pi^-\pi^0$

$K^0_S : K^0_S \to \pi^+\pi^-$

$K^0_{S00} : K^0_S \to \pi^0\pi^0$

Mode	BF (10^{-6})	ϵ (%)	# Evts Selected	Expected Yield
$\eta'_{\eta\pi\pi} K^0_S$	3.9	27	1556	500
$\eta'_{\rho\gamma} K^0_S$	6.6	29	23905	900
$\eta'_{\eta\pi\pi} K^0_{S00}$	1.8	14	1175	110
$\eta'_{\rho\gamma} K^0_{S00}$	3.0	15	28871	200
$\eta'_{5\pi} K^0_S$	2.3	17	546	180
$\eta'_{\eta\pi\pi} K^0_L$	5.7	18	14125	450
$\eta'_{5\pi} K^0_L$	3.3	11	4951	170
$\eta' K^0$	64.9 ± 3.1	–	–	2500

Analysis Overview

1. Reconstruction and Selection:

   - In kinematic fit, reconstruct B candidates from all combinations of tracks and photons.

   - Apply loose selection criteria, which leave < 1.3 candidates per event.

   - Select best B candidate based on B vertex probability.

2. Maximum likelihood fit:

   - Fit samples of 500 - 20k events (depending on decay channel).

   - Characterize event types (signal, backgrounds) using distributions of variables related to decay kinematics and event-shape.

   - Simultaneously

     - isolate signal decays from large background,
     - extract parameters of interest.

3. Potential backgrounds:

   - 99% of background is continuum $e^+e^- \to q\bar{q}\ (q = u, d, s, c)$.
   - Charmless decays from $B\bar{B}$ events in several sub-modes.
   - Charmed B decays in a few sub-modes.

Candidate Reconstruction

- Combine tracks and photons to make B candidates composed of various intermediate resonances.

- In fit to entire decay tree, obtain B decay vertex with resolution of ~0.1 mm.

- Constrain η', η, π^0 masses to nominal values; account for K_S^0 lifetime.
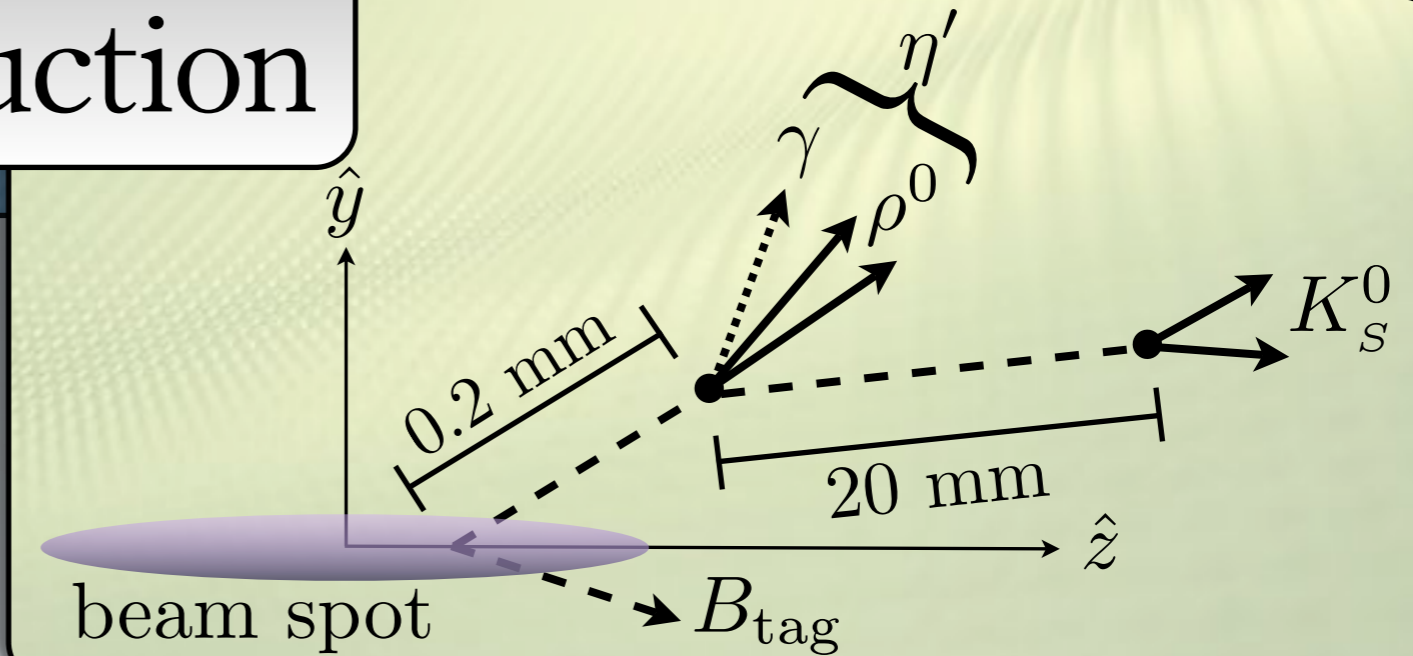
Selection Requirements:

- $N_{\text{trks}} \geq N_{\text{tracks in decay mode}} + 1$,
- $|\Delta E| \leq 0.2$ GeV,
- $5.25 \leq m_{\text{ES}} < 5.2893$ GeV,
- $E_\gamma > 30$ MeV for π^0,
- $E_\gamma > 50$ MeV for $\eta_{\gamma\gamma}$,
- $E_\gamma > 100$ MeV in $\eta'_{\rho\gamma}$,
- $|\cos\theta_\rho| < 0.9$, where θ_ρ is the angle between a ρ^0-daughter π^+ and the η' in the ρ^0 rest frame,

- invariant masses of resonances to be 2-3 widths from nominal mass.
- K_{s+-}^0 vertex fit probability > 0.001,
- K_{s+-}^0 flight length at least 3 times the uncertainty on the flight length,
- $|\Delta t| < 20$ ps,
- $\sigma_{\Delta t} < 2.5$ ps, where $\sigma_{\Delta t}$ is the uncertainty on Δt.

Maximum likelihood fit

- For N measurements of quantities $\mathbf{x}$ distributed according to a *probability density function* (PDF) $\mathcal{P}(\mathbf{x}, \boldsymbol{\alpha})$ where $\boldsymbol{\alpha}$ is a set of parameters, the likelihood is defined:

$$\mathcal{L} \;=\; \prod_{i=1}^{N} \mathcal{P}(\mathbf{x}_i, \boldsymbol{\alpha})$$

- Given the data $\mathbf{x}_i$, the maximum of $\mathcal{L}$ over $\boldsymbol{\alpha}$ gives an unbiased estimate of $\boldsymbol{\alpha}$.

- For m components of the data, each of fraction f_j ($\sum f_j = 1$), the PDF has form:

$$\mathcal{P}(\mathbf{x}_i, \boldsymbol{\alpha}) = \sum_{j=1}^{m} f_j \mathcal{P}_j(\mathbf{x}_i, \boldsymbol{\alpha}_j)$$

- Since N is randomly distributed, include Poisson factor for making N measurements when expecting $\sum \nu_j$:

$$\mathcal{L} = \frac{e^{-(\sum \nu_j)}}{N!} \prod_{i=1}^{N} \sum_{j=1}^{m} \nu_j \mathcal{P}_j(\mathbf{x}_i, \boldsymbol{\alpha}_j)$$

ML fit specifics

- Correlations between variables of $\mathbf{x}$ are low (<5%), so we factorize the PDF for each fit component j:

$$\mathcal{P}_j(\mathbf{x}, \boldsymbol{\alpha}_j) = \mathcal{P}_j(x_1, \boldsymbol{\alpha}_{1,j})\mathcal{P}_j(x_2, \boldsymbol{\alpha}_{2,j})...\mathcal{P}_j(x_n, \boldsymbol{\alpha}_{n,j})$$

- Minimize $-\ln \mathcal{L}$ instead of maximizing $\mathcal{L}$.

- The first task of the ML fit is determine n PDFs for m fit components.

- The m fit components are:
  1. Signal (sig).
  2. Continuum ($q\bar{q}$).
  3. Charmless $B\bar{B}$ (chls) for some modes.
  4. Charmed $B\bar{B}$ (chrm) for some modes.

- The n observables:
  1. Kinematic quantities (m_{ES}, ΔE).
  2. Event-shape Fisher discriminant ($\mathcal{F}$).
  3. Time-difference (Δt).

Kinematic variables: $m_{\mathrm{ES}}, \Delta E$
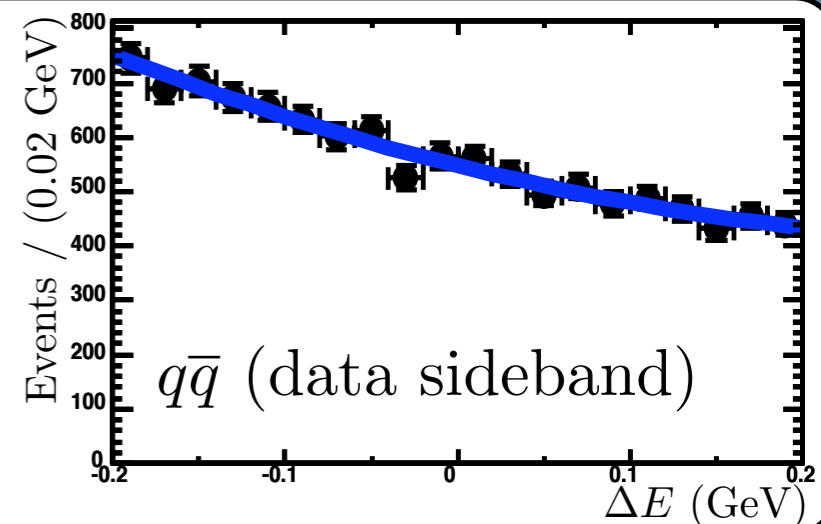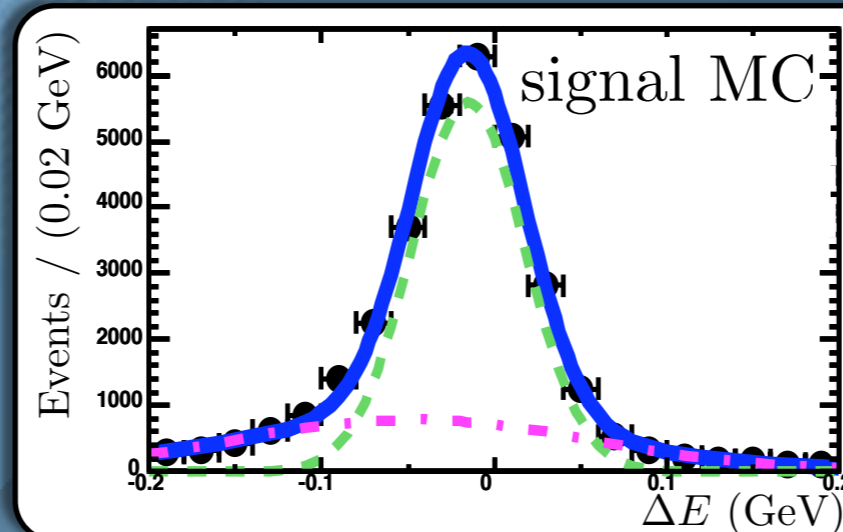
Beams 4-momentum:

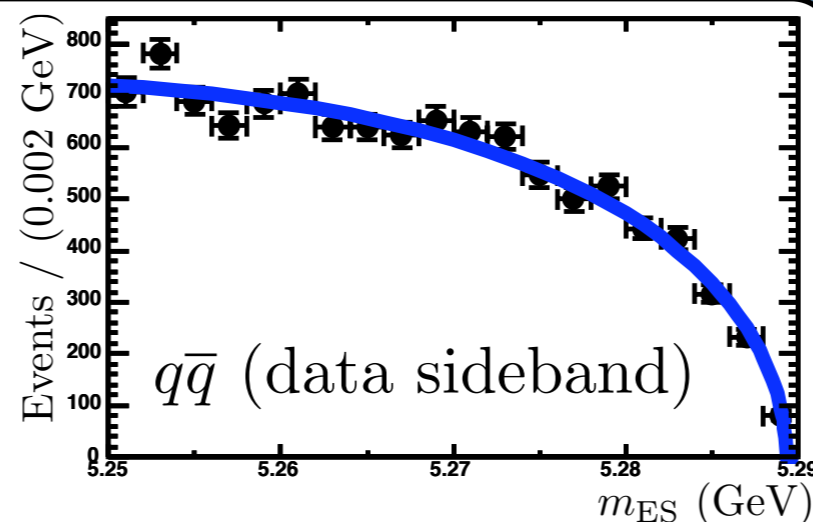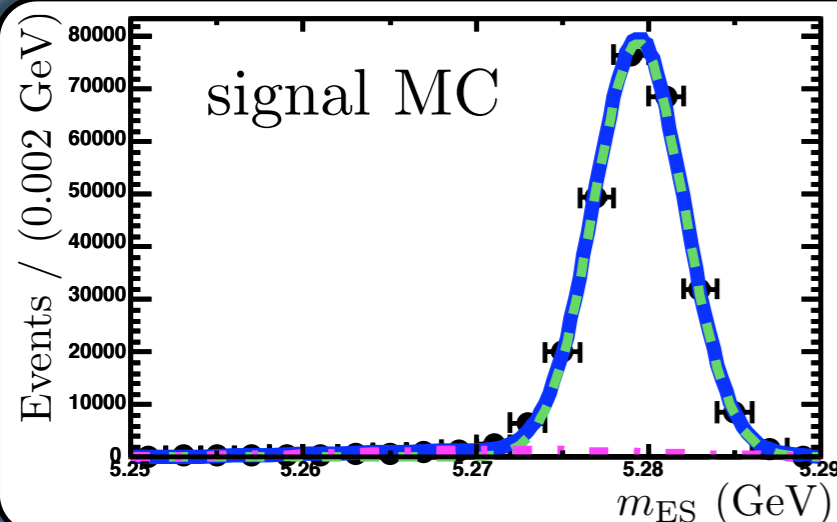$$q_0 = (E_0, \mathbf{p}_0)$$

Signal B 4-momentum:

$$q_B = (E_B, \mathbf{p}_B)$$

$$s \equiv q_0^2$$

$*$ Denotes CM frame.
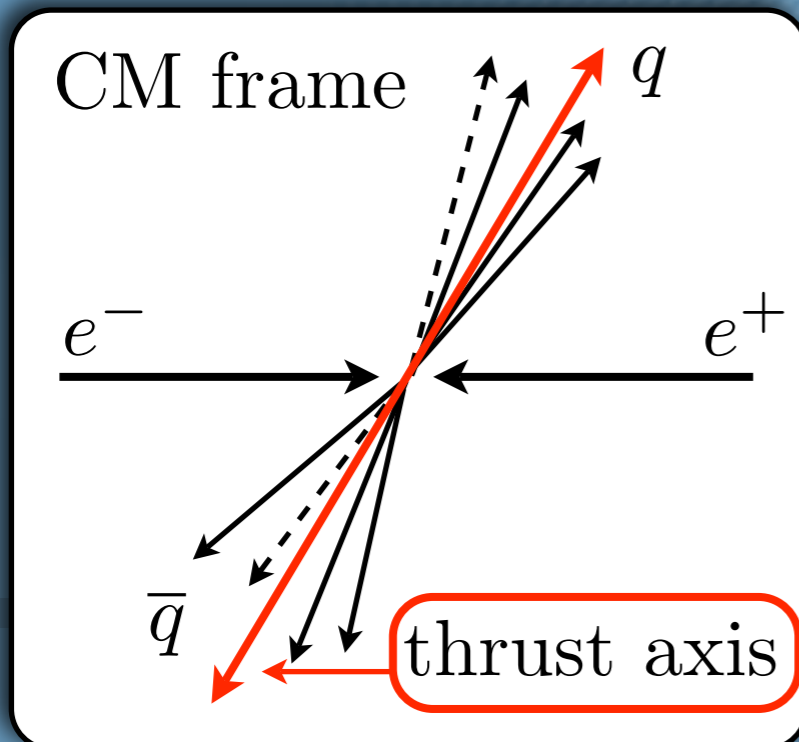
$$\Delta E = E_B^* - \frac{1}{2} E_0^*$$

Designed to be uncorrelated.

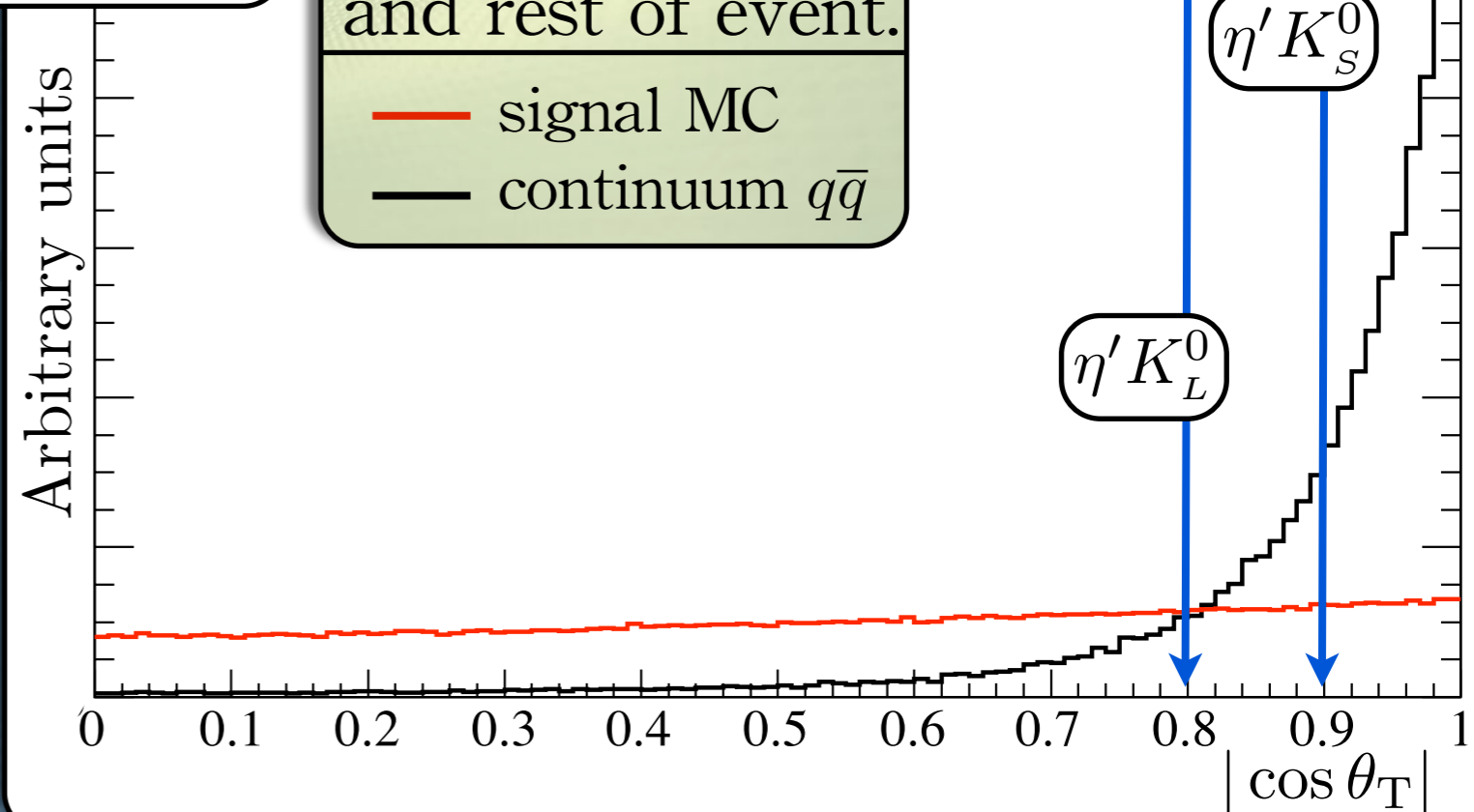Lab quantities require no mass hypothesis.

$$m_{\mathrm{ES}} = \sqrt{(\tfrac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2 / E_0^2 - p_B^2} = \sqrt{\tfrac{s}{4} - p_B^{*2}}$$
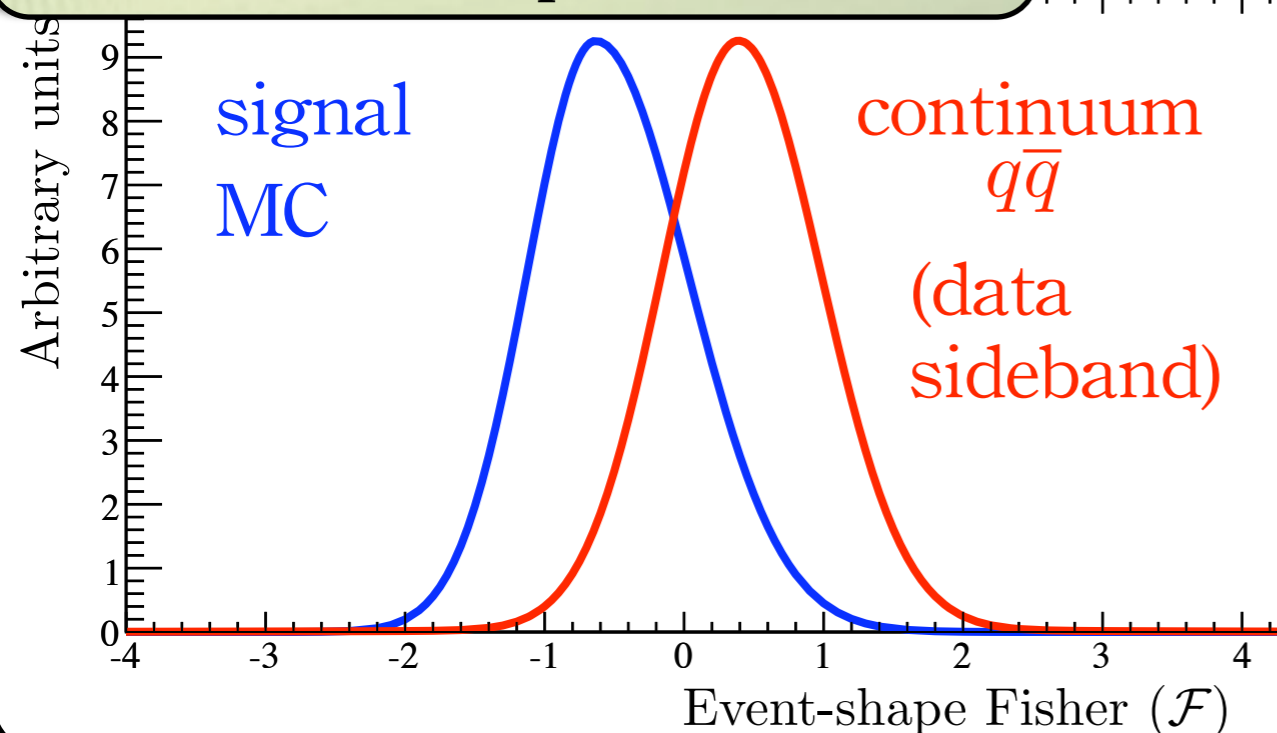

signal MC

$q\bar{q}$ (data sideband)

signal MC

$q\bar{q}$ (data sideband)

Event-shape variables

CM frame

q

e^- e^+

$\bar{q}$

thrust axis

Cut on angle b/w thrust axes of B and rest of event.

— signal MC
— continuum $q\bar{q}$

Arbitrary units

$\eta' K_S^0$

$\eta' K_L^0$

$|\cos\theta_{\mathrm{T}}|$

Fisher discriminant ($\mathcal{F}$) of other event-shape variables:

signal MC

continuum $q\bar{q}$

(data sideband)

Arbitrary units

Event-shape Fisher ($\mathcal{F}$)

1. Angle w.r.t. beams of B momentum.
2. Angle w.r.t. beams of B thrust axis.
3. Zeroth angular moment L_0.
4. Second angular moment L_2.
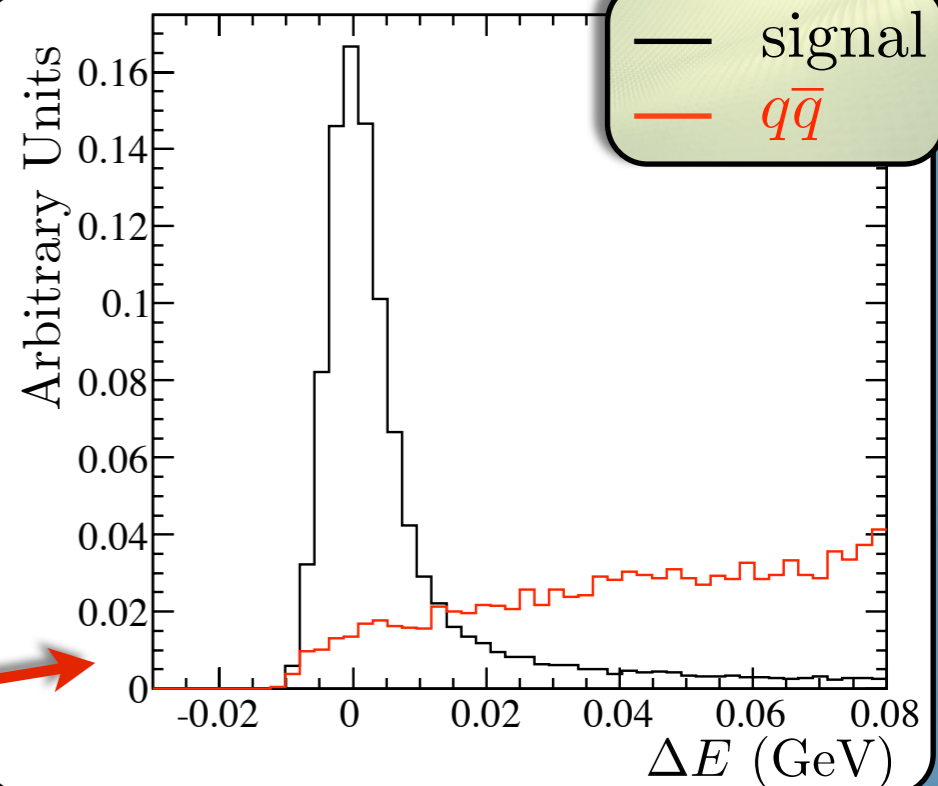
$$L_i = \sum_j p_j \times |\cos\theta_j|^i$$

p_j momentum of jth particle in event.

θ_j angle wrt B thrust axis of particle j.

Sum excludes B daughters.

K_L^0 Reconstruction

- K_L^0`s detected in EMC (60%) and IFR (40%).

- Can`t reconstruct K_L^0 4-momentum, obtain K_L^0 direction from η' decay vertex and centroid of EMC/IFR cluster.

- Constrain masses of B and K_L^0 in vertexing.

- $m_{ES}/\Delta E$ 100% correlated; only ΔE in ML fit.

Three cuts to reduce $q\bar{q}$, optimized for precision on S and C:
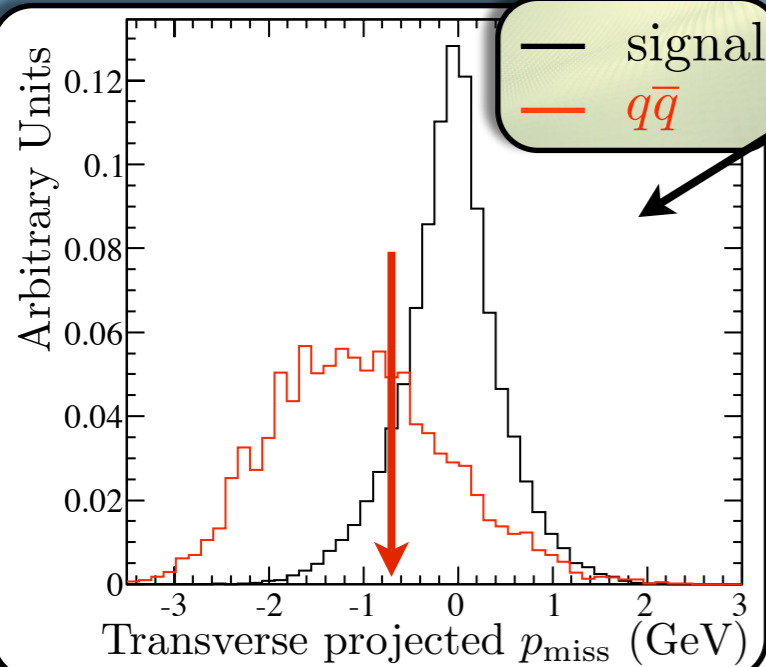
1. Magnitude of missing momentum p_{miss}.

2. Angle wrt beams of missing momentum $\cos\theta_{p_{miss}}$.

3. Output of neural network of EMC shower-shape quantities.

Charmless $B\bar{B}$ background

charmless MC

$m_{\rm ES}$ (GeV)

- Background (BG) events from charmless $B\bar{B}$ decays have broad peaks in ΔE and $m_{\rm ES}$
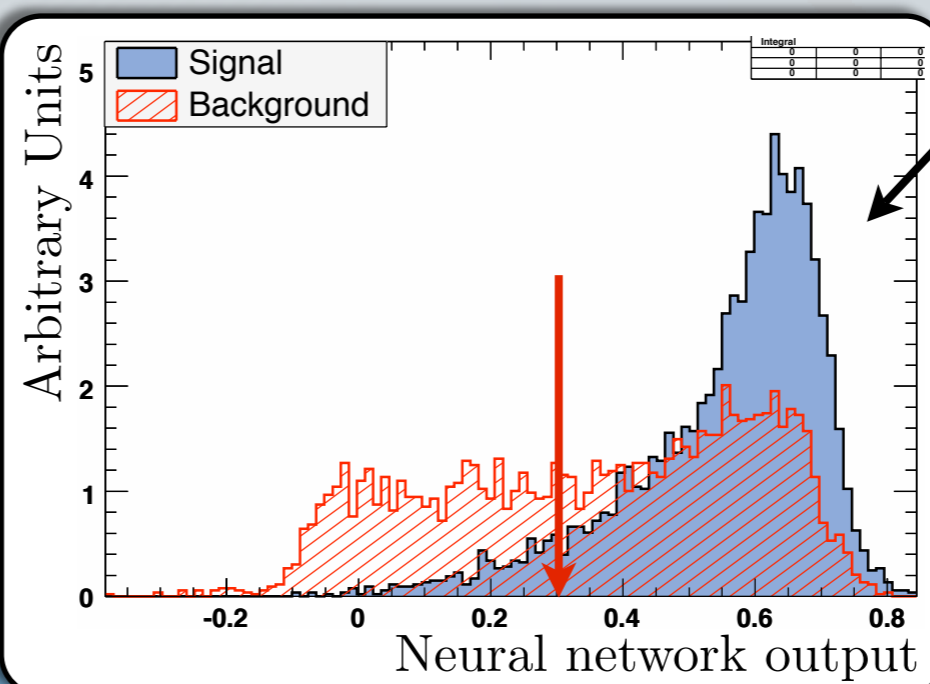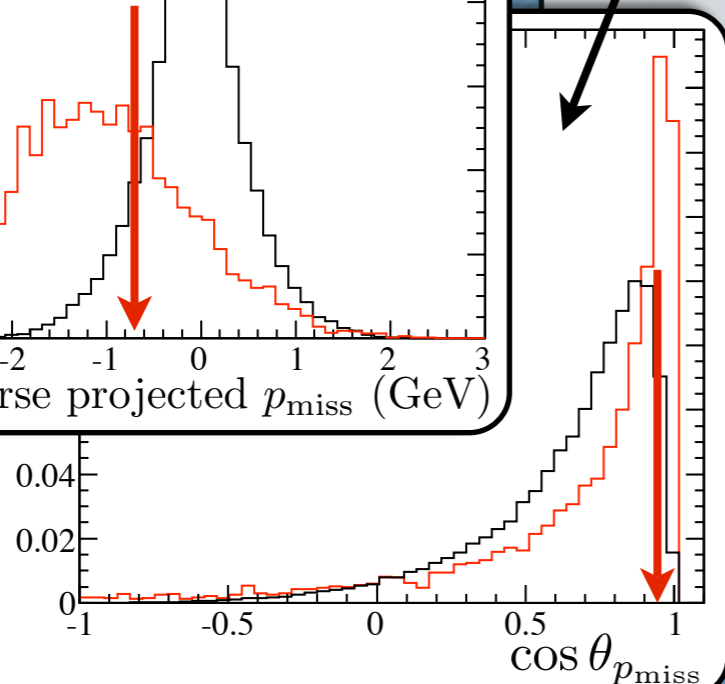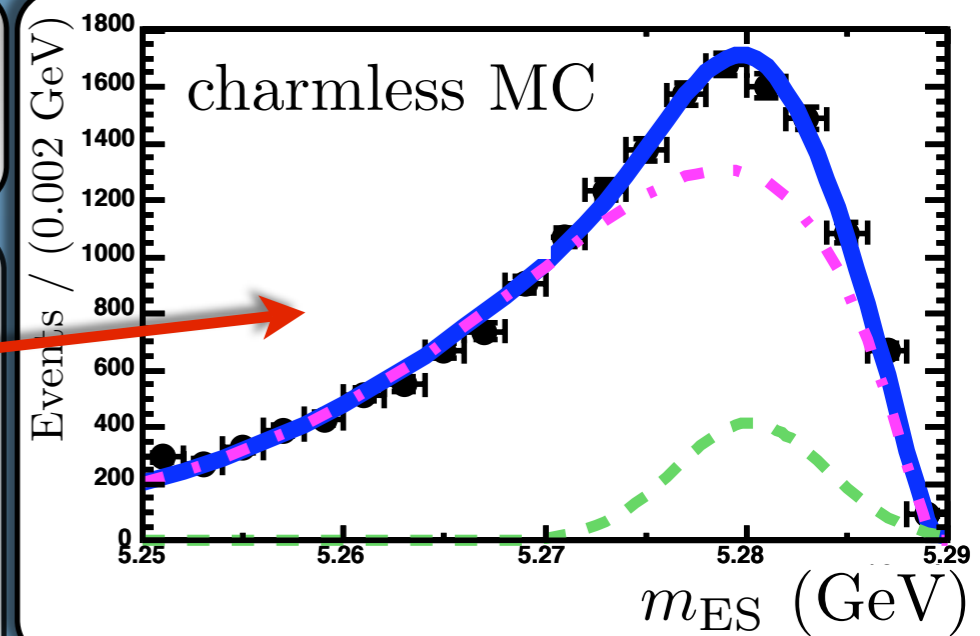
- Identify BG modes with generic $B\bar{B}$ MC.

- Use exclusive MC for identified modes and known BF`s to model charmless background.

- Example from $B^0 \to \eta'_{\rho\gamma} K^0_S$:

Bkg. channel	MC ϵ (%)	Est. $\mathcal{B}$ (10^{-6})	$\prod \mathcal{B}_i$	Norm. # $B\bar{B}$ Bkg.	# in PDF Bkg. file
$B^+ \to a_1^+(\rho^0\pi^+)K^0$	2.25	$34.9^{+6.7}_{-6.7}$	0.231	83.4	5290
$B^0 \to \pi^+\pi^- K^0$	1.14	$44.8^{+2.6}_{-2.5}$	0.346	81.2	5145
$B^0 \to a_1^0(\rho^-\pi^+)K^0$	2.08	15^*	0.231	33.1	2100
$B^+ \to \rho^+ K^0$	0.82	$8.0^{+1.5}_{-1.4}$	0.500	15	950
$B^0 \to \phi_{3\pi} K^0$	6.32	$8.3^{+1.2}_{-1.0}$	0.053	12.8	809
$B^+ \to a_1^+(\rho^+\pi^0)K^0$	0.46	$34.9^{+6.7}_{-6.7}$	0.115	8.5	537
$B^+ \to \rho\, K_0^*(1430)$	0.05	40^*	1.000	8.3	529
$B^+ \to \rho^0 K^{*+}_{K^0_S\pi^+}$	1.6	$3.6^{+1.9}_{-1.8}$	0.231	6.1	387
$B^0 \to K^+K^- K^0$	0.13	$24.7^{+2.3}_{-2.3}$	0.346	5	316
$B^0 \to \rho\, K_0^*(1430)$	0.05	20^*	1.000	4.6	292
$B^0 \to \omega\, K^0$	0.61	$5.1^{+0.6}_{-0.6}$	0.308	4.4	279
$B^+ \to \eta'_{\rho\gamma} K^{*+}_{K^0_S\pi^+}$	2.67	$4.9^{+2.1}_{-1.9}$	0.067	4	255
Total				279.4	17463

Expected charmless BG for each sub-decay mode:

Mode	# Events
$\eta'_{\eta\pi\pi} K_S$	< 5
$\eta'_{\rho\gamma} K_S$	279
$\eta'_{\eta\pi\pi} K_{S00}$	< 5
$\eta'_{\rho\gamma} K_{S00}$	69
$\eta'_{5\pi} K_S$	< 5
$\eta'_{\eta\pi\pi} K_L$	22
$\eta'_{5\pi} K_L$	< 5

Chls BG entering fit, to be discriminated against ~1000 signal events.

$B^0 \to \eta'_{\rho\gamma} K_S^0$ PDFs
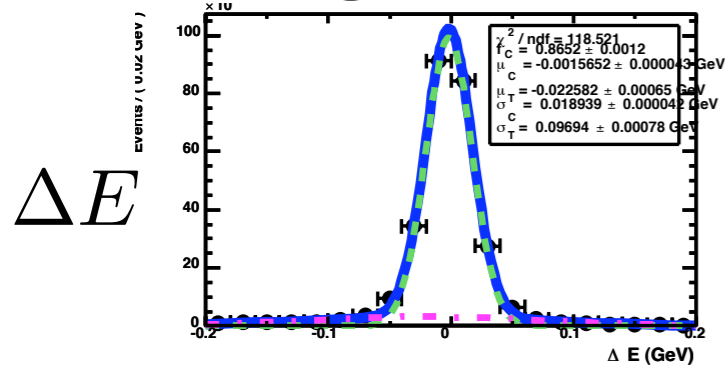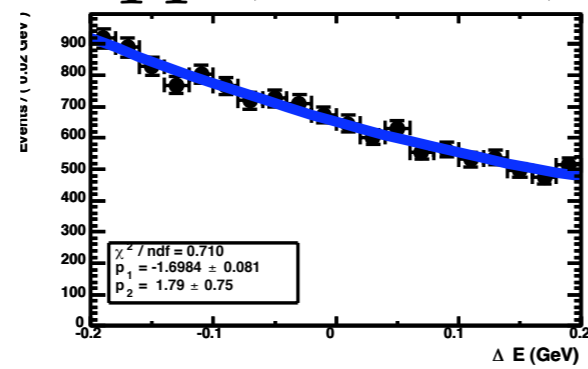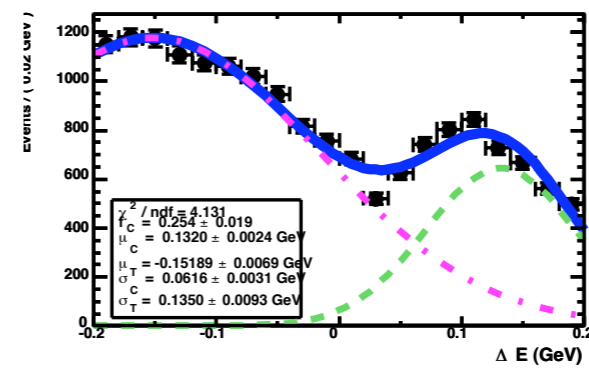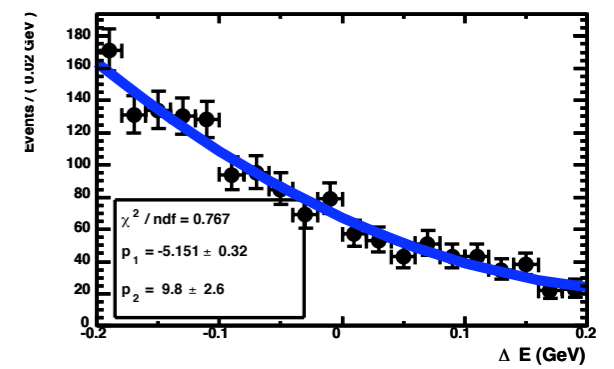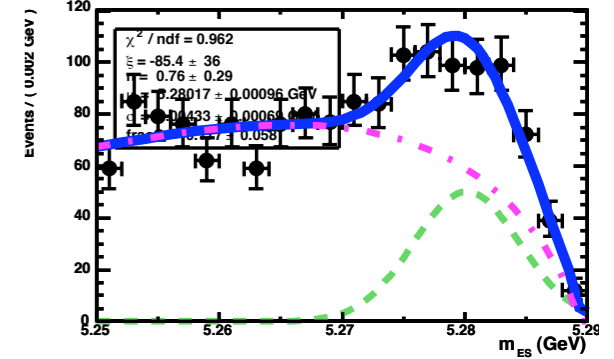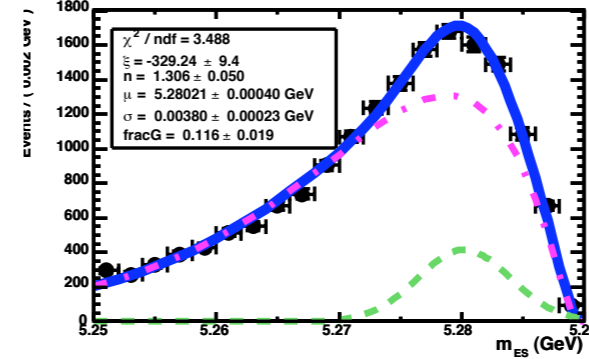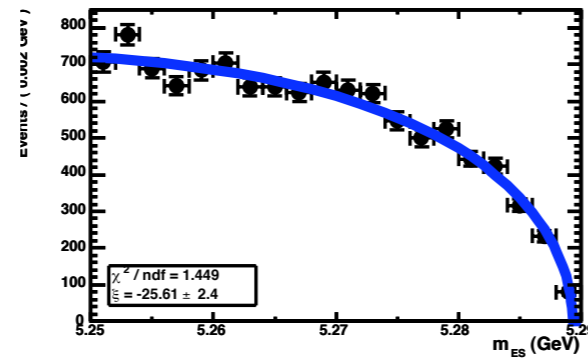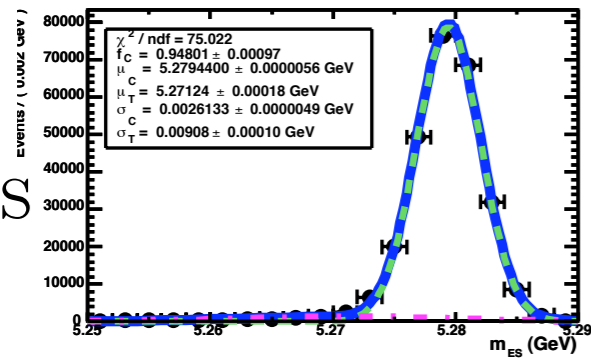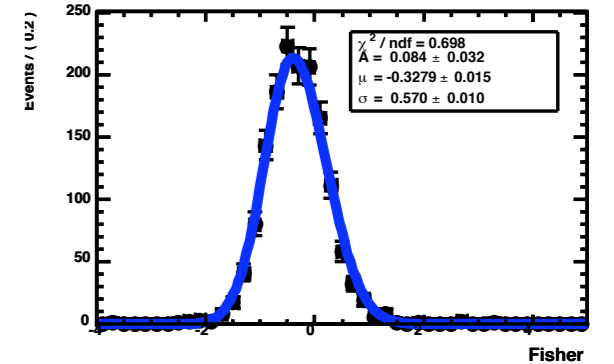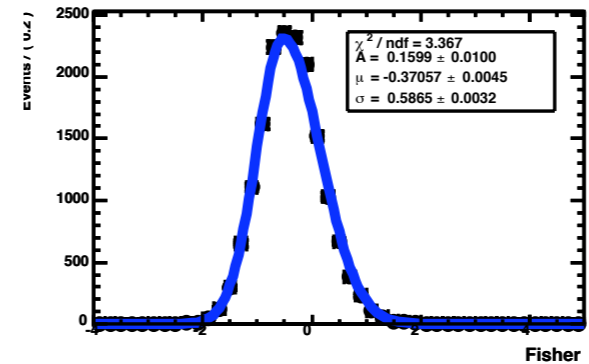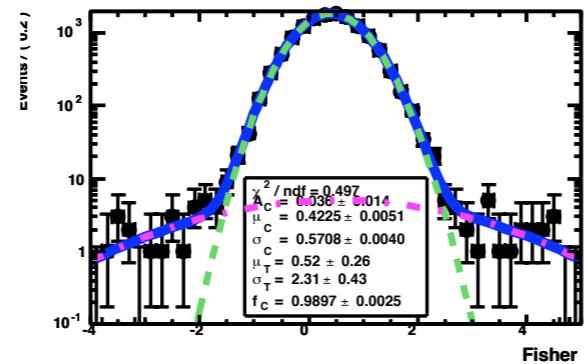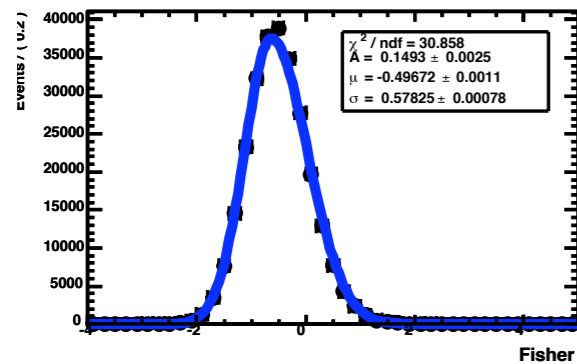
Time-dependent analysis

- Measure Δz, convert to Δt using boost, p^μ of B_{CP} , τ_{B^0} .
- Determine flavor of B_tag with tagging algorithm (next slide).

- Δt and tag ($\pm$) go into:
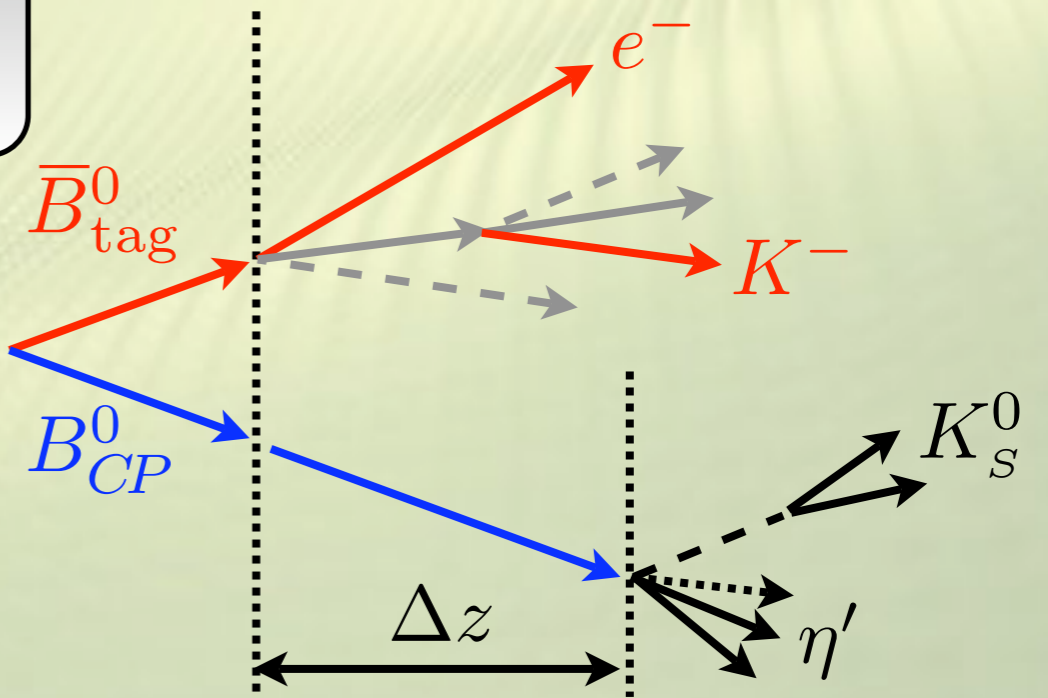
$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 \mp \eta_f S_f \sin(\Delta m_B \Delta t) \mp C_f \cos(\Delta m_B \Delta t)\right]$$

- Modify $f_\pm$ for tagging performance:

$$f'_\pm = (1 - w_\pm)f_\pm + w_\mp f_\mp$$

$w_+ \ (w_-)$: wrong tag probability for true B^0 $(\overline{B}{}^0)$
$\Delta w \equiv w_+ - w_-$, $w \equiv (w_+ + w_-)/2$

$$f'_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left\{1 \mp \Delta w \pm (1-2w)\left[-\eta_f S_f \sin(\Delta m_B \Delta t) - C_f \cos(\Delta m_B \Delta t)\right]\right\}$$

- Modify $f'_\pm$ for tagging efficiency asymmetry (μ) for B^0 and $\overline{B}{}^0$.

- Convolve $f'_\pm$ with Δt resolution function to obtain final Δt PDF:

$$\mathcal{P}_\pm(\Delta t | \sigma_{\Delta t}) = f'_\pm(\Delta t) \otimes \mathcal{R}(\Delta t, \sigma_{\Delta t})$$

Tagging algorithm

Semileptonic B decay

$$\bar{b} \xrightarrow{\quad W^+ \quad} \bar{c}, \quad W^+ \to l^+ \nu_l$$

$$d \longrightarrow d$$

- Neural-network-based algorithm assigns each B_{tag} candidate to 1 of 6 categories.

- Category is determined by continuous output of algorithm (and lepton in the B_{tag} final state).

- Cleanest tagging from semileptonic decays, such as $B^0 \to D^{*-} l^+ \nu_l$.

- Clean tagging from $b \to c \to s$ decays, such as $B^0 \to D^{*-} \rho^+, \; D^{*-} \to \overline{D}^0 \pi^-, \; \overline{D}^0 \to K^+ \pi^-$
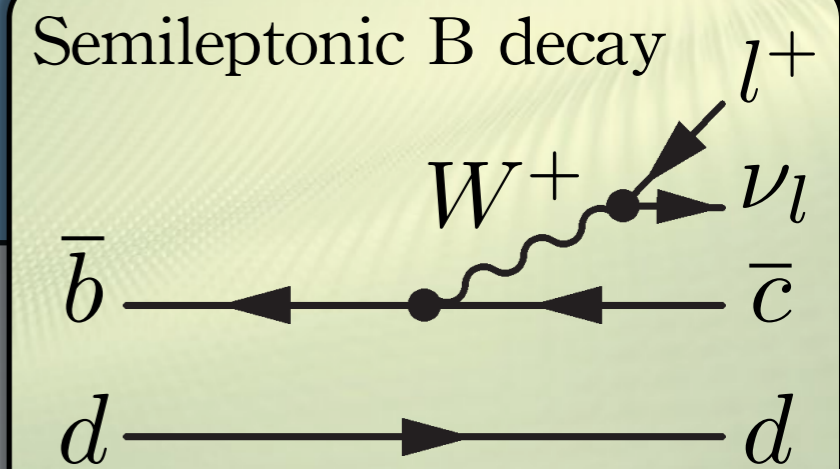
- Mistagging and experimental Δt resolution change <u>ideal</u> into <u>observed</u> Δt distribution.

Ideal

B^0 tags
B̄^{0} tags

arbitrary scale

Observed

B^0 tags
B̄^{0} tags

-5   0   5

Δt (ps)
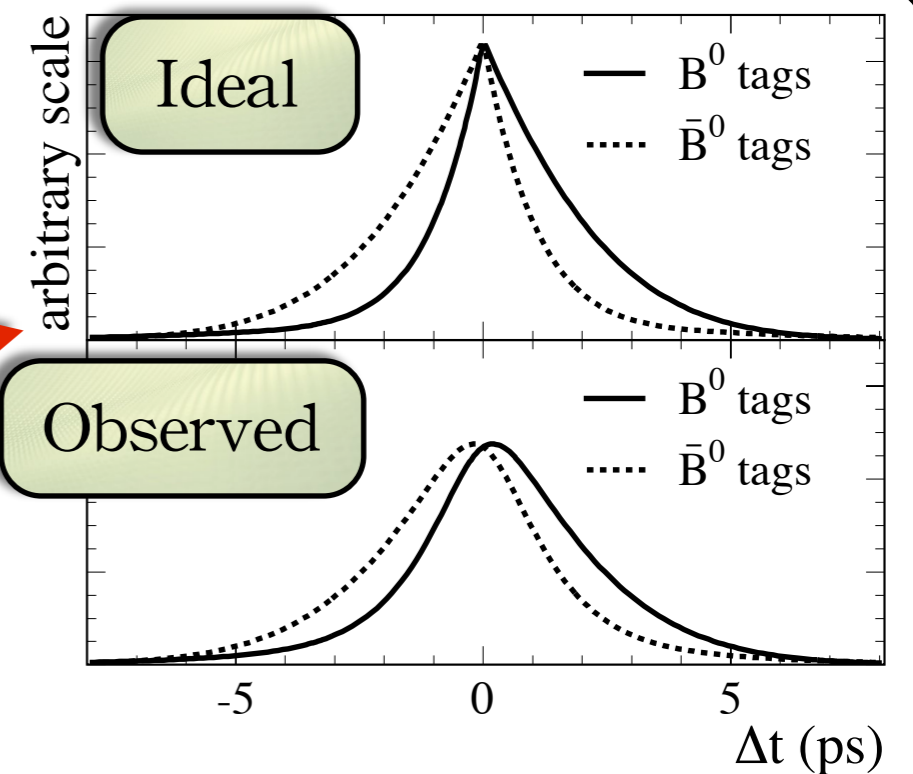
B_{flav} Sample

- How do we get parameters for tagging ($\epsilon,\ w,\ \Delta w,\ \mu$) and $\mathcal{R}(\Delta t, \sigma_{\Delta t})$?
  - The performance of the tagging algorithm is independent of signal mode.
  - Resolution on Δt is dominated by tag-side vertex.
- B_{flav} sample : 100k (c.f. 2.5k signal events) fully reconstructed, self-tagging decays $B^0 \to D^{(*)-}(\pi^+,\ \rho^+,\ a_1^+)$.
- Fit B_{flav} sample to determine tagging and resolution model parameters.
  - No dependence on MC.

ϵ : probability to be tagged
$\mu \equiv \epsilon(B^0) - \epsilon(\bar{B}^0)$
$Q \equiv \epsilon(1 - 2w)^2$
$\sigma_{S,C} \propto 1/\sqrt{Q}$

Category	ϵ (%)	w (%)	Δw (%)	μ (%)	Q (%)
Lepton	9.0 ± 0.1	2.8 ± 0.3	0.3 ± 0.5	-0.3 ± 0.9	8.0 ± 0.1
Kaon I	10.8 ± 0.1	5.3 ± 0.3	-0.1 ± 0.6	0.1 ± 0.9	8.7 ± 0.1
Kaon II	17.2 ± 0.1	14.5 ± 0.3	0.4 ± 0.6	0.6 ± 0.8	8.7 ± 0.2
Kaon-Pion	13.7 ± 0.1	23.3 ± 0.4	-0.7 ± 0.7	0.2 ± 0.9	3.9 ± 0.1
Pion	14.2 ± 0.1	32.5 ± 0.4	5.1 ± 0.7	-2.5 ± 0.9	1.7 ± 0.1
Other	9.5 ± 0.1	41.5 ± 0.5	3.8 ± 0.8	1.8 ± 1.0	0.3 ± 0.0
All	74.4 ± 0.1				31.2 ± 0.3

75% of events are tagged.

30% effective rate due to mistagging.

Grand Simultaneous Fit

| c : tagging category |
| N_c : events in c |
| ϵ_c : tag efficiency for c |

- For each sub-mode f, $\mathcal{L}_f$ is product of $\mathcal{L}_{c,f}$ for each tagging category:

$$\mathcal{L}_f = \prod_{c=0}^{6} \frac{e^{(-\sum_j \nu_{j,c})}}{N_c!} \prod_i^{N_c} (\nu_{\text{sig}}\epsilon_c \mathcal{P}_{\text{sig},c}^i + \nu_{q\bar{q},c}\mathcal{P}_{q\bar{q}}^i + \nu_{\text{chls}}\epsilon_c \mathcal{P}_{\text{chls},c}^i + \nu_{\text{chrm}}\epsilon_c \mathcal{P}_{\text{chrm},c}^i).$$

We average sub-mode results by maximizing product of $\mathcal{L}_f$`s while constraining all $-\eta_f S_f$ to a single value, $S_{\eta'K^0}$.

133 free parameters !!

non-Δt PDFs:
- Event yields for sig, $q\bar{q}$, chrm, are free.
- Parameters of $q\bar{q}$ are free in fit.
- sig, chrm, chls parameters fixed to values from MC.

Mode	Components
$\eta'_{\eta\pi\pi}K_S$	sig, $q\bar{q}$
$\eta'_{\rho\gamma}K_S$	sig, $q\bar{q}$, chls*, chrm
$\eta'_{\eta\pi\pi}K_{S00}$	sig, $q\bar{q}$
$\eta'_{\rho\gamma}K_{S00}$	sig, $q\bar{q}$, chls*, chrm
$\eta'_{5\pi}K_S$	sig, $q\bar{q}$
$\eta'_{\eta\pi\pi}K_L$	sig, $q\bar{q}$, chls*
$\eta'_{5\pi}K_L$	sig, $q\bar{q}$ *fixed yield

Δt models

| | | Parameter Source | | |
Component	Tagging	$\mathcal{R}(\Delta t)$	S, C
sig	B_{flav}	B_{flav}	free
$q\bar{q}$	τ_B fixed to 0	free	n/a
chls	B_{flav}	chls MC	fixed to 0
chrm	B_{flav}	chrm MC	fixed to 0

Fit validation : toy MC experiments

- Perform 150-550 simulated experiments using toy datasets:
  - Generate $q\bar{q}$ and charmed $B\bar{B}$ events from factorized PDFs,
  - Embed MC events for signal and charmless $B\bar{B}$.
- Estimate bias due to correlations in signal and residual contributions of backgrounds and misreconstructed signal.
- Confirm that uncertainties reported by fit are reasonable.

Final state	# toy experiments	# sig input	# chls input	Signal Bias	Bias on S	Bias on C
$\eta'_{\eta\pi\pi}K^0_S$	550	470	0	-3.7 ± 0.5	0.010 ± 0.007	-0.012 ± 0.005
$\eta'_{\rho\gamma}K^0_S$	260	970	279	35.1 ± 1.4	0.002 ± 0.007	-0.007 ± 0.006
$\eta'_{\eta\pi\pi}K^0_{S00}$	200	108	0	-3.0 ± 0.6	0.080 ± 0.034	0.022 ± 0.020
$\eta'_{\rho\gamma}K^0_{S00}$	270	199	69	7.3 ± 1.3	0.054 ± 0.022	-0.007 ± 0.016
$\eta'_{5\pi}K^0_S$	190	173	0	-1.8 ± 0.4	0.021 ± 0.020	-0.009 ± 0.014
$\eta'_{\eta\pi\pi}K^0_L$	235	353	22	-25.3 ± 1.7	-0.019 ± 0.018	-0.007 ± 0.013
$\eta'_{5\pi}K^0_L$	140	170	0	-9.5 ± 1.5	0.099 ± 0.035	0.007 ± 0.022
Weighted Avg.					0.013 ± 0.004	-0.007 ± 0.003
Simultaneous $\eta'K^0$ Fit	175			**unbiased fit**	0.006 ± 0.006	-0.008 ± 0.006
Simultaneous $\eta'K^0_S$ Fit	175				0.008 ± 0.006	-0.007 ± 0.005
Simultaneous $\eta'K^0_L$ Fit	175				0.003 ± 0.014	-0.006 ± 0.011

Systematic Errors

PDF parameterization:

- Vary fixed parameters by amounts found in studies of data control samples (B_{flav}, $B^- \to D^0 \pi^-$, $B^+ \to \eta' K^+$) .

BB background:

- Vary S and C for chls, chrm components.

- Vary fixed charmless yields by $\pm 20\%$.

Signal Δt parameterization :

- Comparing toy MC studies performed with Δt parameters ($\mathcal{R}(\Delta t)$ and tagging) from signal and B_{flav} MC.

- Estimate effects due to differences between signal and B_{flav} data.

Source of error	$\sigma(S)$	$\sigma(C)$
Beam position/size	0.002	0.001
SVT alignment	+0.002 / −0.001	+0.003 / −0.002
Tag-side interference	0.001	0.015
Self-crossfeed	0.006	0.003
Fit Bias	0.006	0.006
PDF Shapes	0.005	0.009
$B\bar{B}$ Background	0.008	0.004
Signal Δt Shape	0.009	0.010
Total	0.016	0.022

$B^0 \to \eta' K^0$ Results

	$\eta'_{\eta\pi\pi} K^0_S$	$\eta'_{\rho\gamma} K^0_S$	$\eta'_{\eta\pi\pi} K^0_{S00}$	$\eta'_{\rho\gamma} K^0_{S00}$	$\eta'_{5\pi} K^0_S$	$\eta'_{\eta\pi\pi} K^0_L$	$\eta'_{5\pi} K^0_L$
Events to fit	1470	22775	1056	27057	513	12217	4586
Signal yield	472 ± 24	1005 ± 40	105 ± 13	206 ± 28	171 ± 14	341 ± 32	158.7 ± 21.6
Chls yield	–	279	–	69	–	22	–
Chrm yield	–	253 ± 67	–	530 ± 84	–	–	–
$-\eta_f S_f$	0.70 ± 0.17	0.46 ± 0.12	0.51 ± 0.34	0.26 ± 0.33	0.76 ± 0.26	0.65 ± 0.22	0.66 ± 0.46
C_f	-0.17 ± 0.11	-0.13 ± 0.09	-0.19 ± 0.30	0.04 ± 0.26	0.05 ± 0.20	0.07 ± 0.19	0.02 ± 0.26

Combined:

$$S_{\eta' K^0_S} = 0.537 \pm 0.084$$
$$C_{\eta' K^0_S} = -0.118 \pm 0.062$$

$$-1 \cdot S_{\eta' K^0_L} = 0.642 \pm 0.198$$
$$C_{\eta' K^0_L} = 0.047 \pm 0.154$$

$$S_{\eta' K^0} = 0.551 \pm 0.777$$
$$C_{\eta' K^0} = -0.094 \pm 0.058$$

- With about 1500 $B^0 \to \eta' K^0_S$ and 300 $B^0 \to \eta' K^0_L$ flavor-tagged decays, we find these bias-corrected results:

$$
\begin{aligned}
S_{\eta' K^0} &= 0.545 \pm 0.077 \pm 0.016 \\
C_{\eta' K^0} &= -0.086 \pm 0.058 \pm 0.022 \\
S_{\eta' K^0_S} &= 0.529 \pm 0.084 \pm 0.016 \\
C_{\eta' K^0_S} &= -0.111 \pm 0.062 \pm 0.024 \\
S_{\eta' K^0_L} &= 0.639 \pm 0.198 \pm 0.033 \\
C_{\eta' K^0_L} &= 0.053 \pm 0.154 \pm 0.029
\end{aligned}
$$

$B^0 \rightarrow \eta' K_L^0$ Results
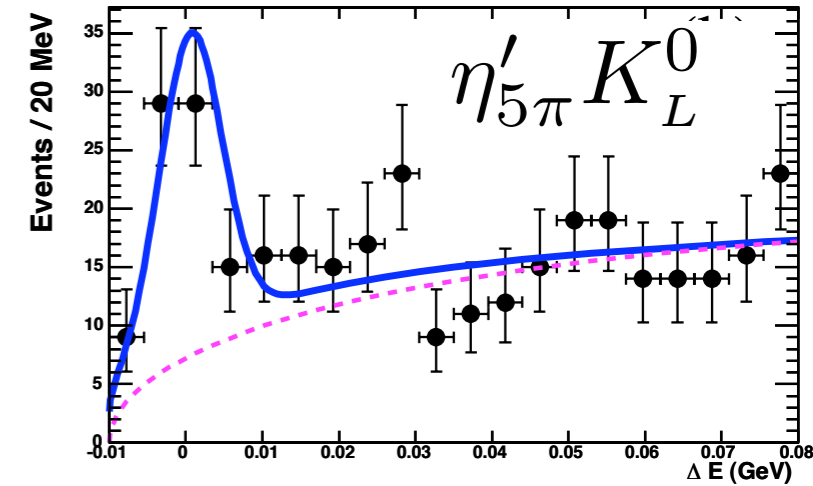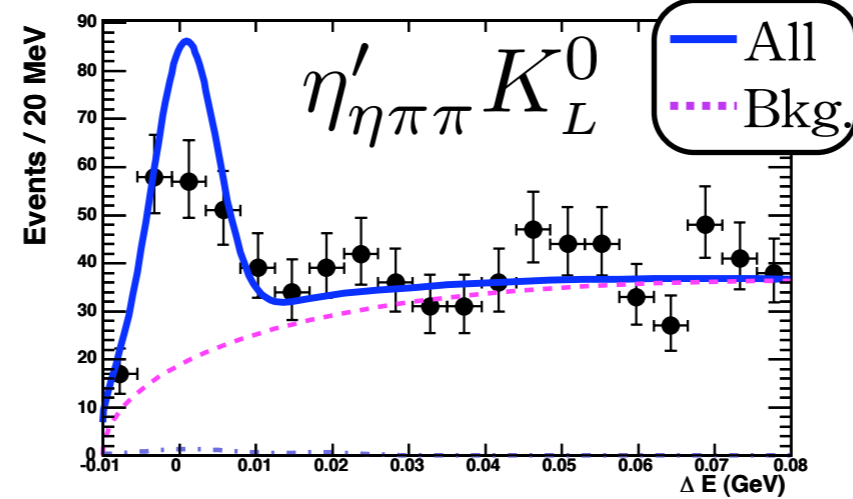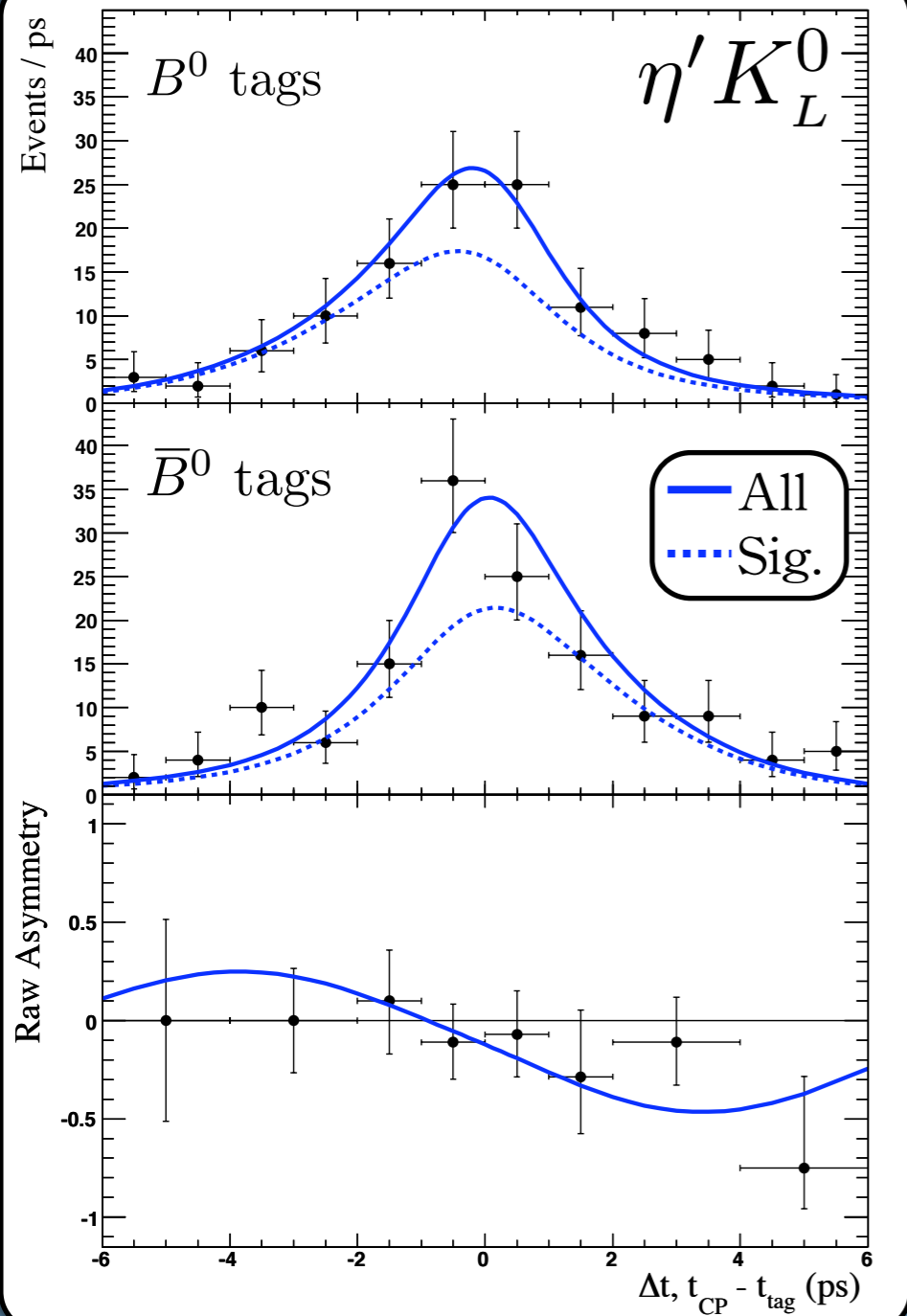
Signal-enhanced projections

Projections of ΔE and Δt with optimized, mode-dependent requirement on

$$\frac{\mathcal{L}_\mathrm{S}}{\mathcal{L}_\mathrm{S} + \mathcal{L}_\mathrm{B}}$$

to enhance the signal.

$B^0 \to \eta' K_S^0$ Results
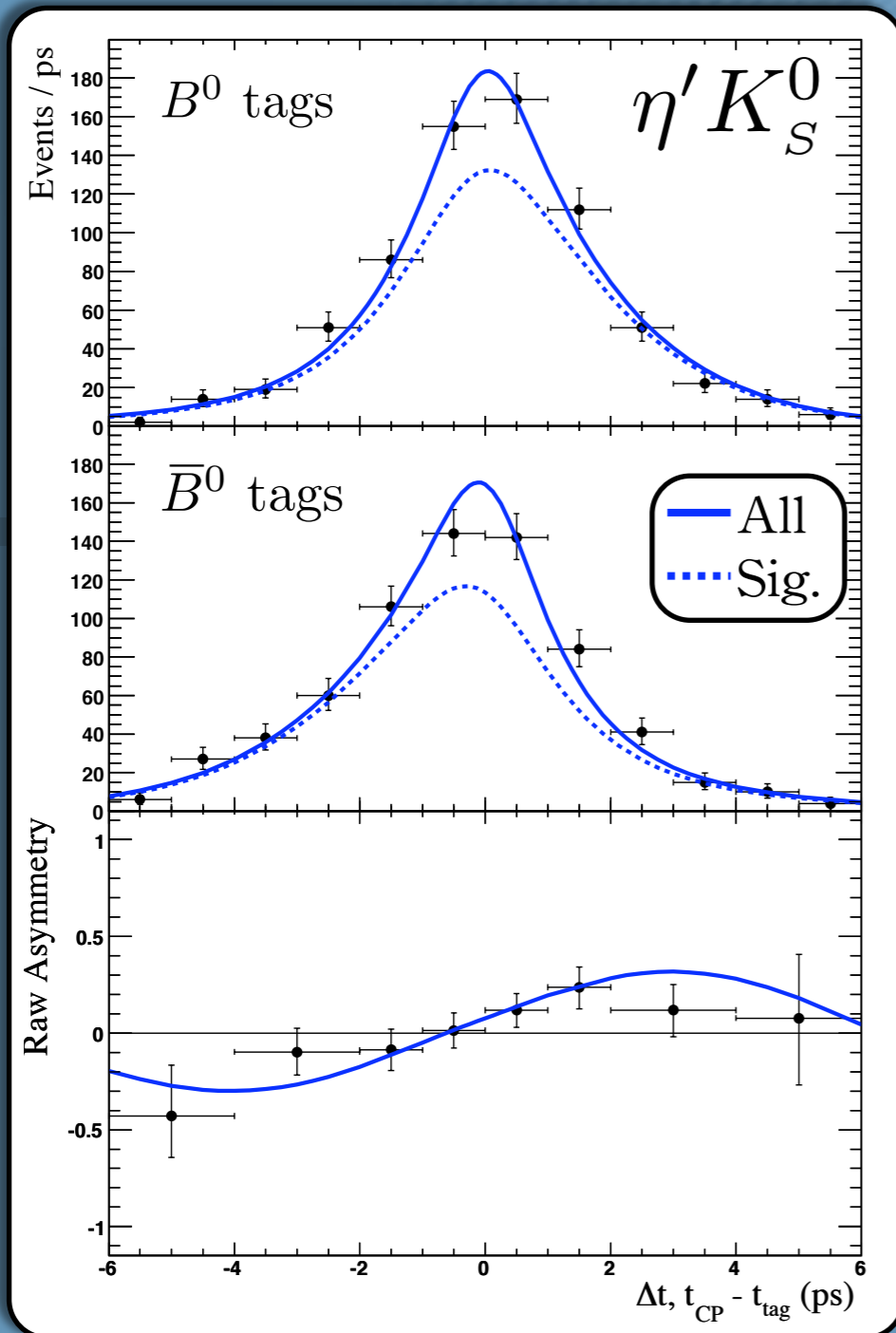
Signal-enhanced projections of m_{ES}, ΔE, and Δt

$B^0 \rightarrow \omega K^0_S$
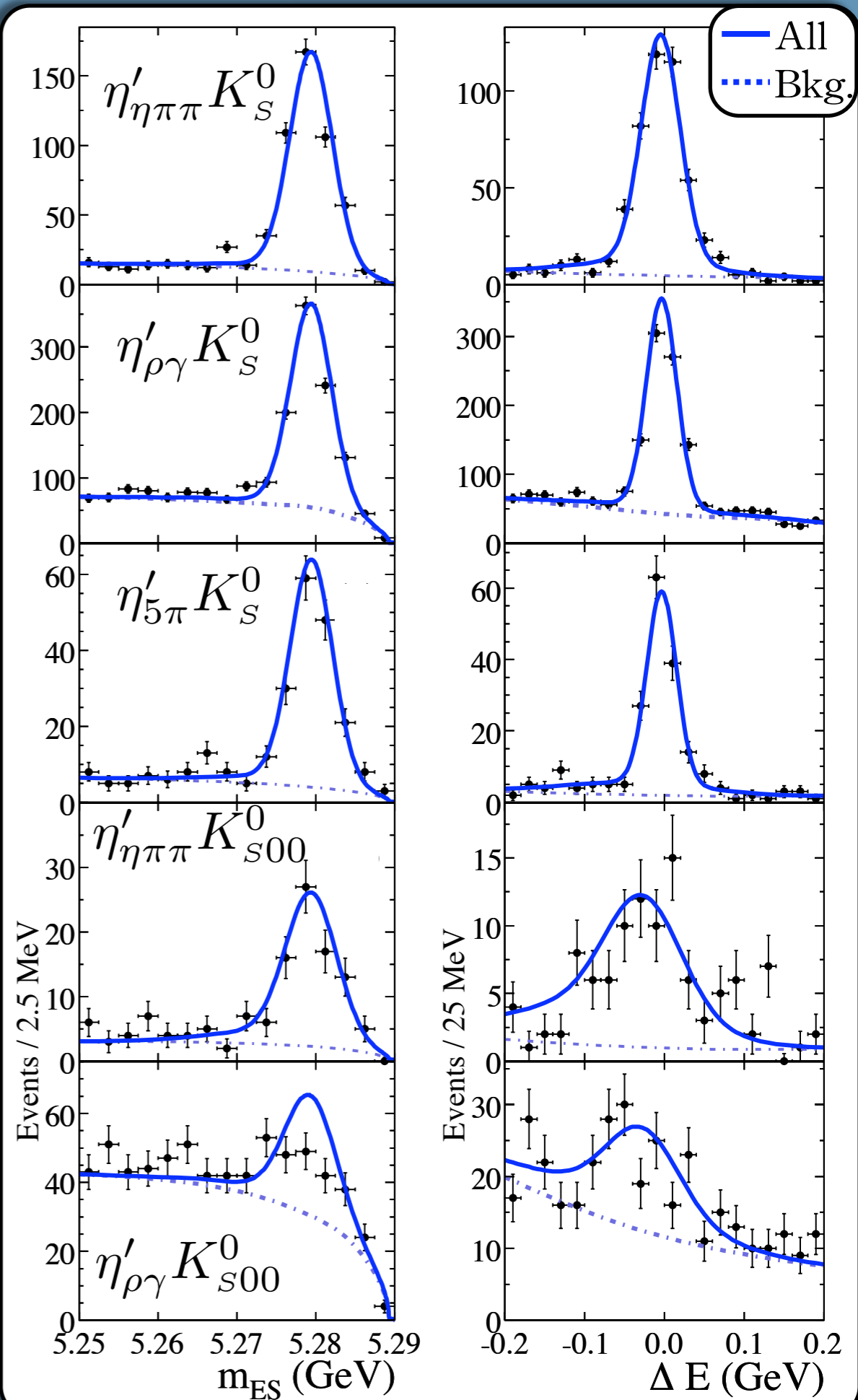
arXiv:0809.1174 (submitted to PRD)

- 163 ± 18 signal events with $\omega \rightarrow \pi^+\pi^-\pi^0$ and $K^0_S \rightarrow \pi^+\pi^-$

$$S = 0.55^{+0.26}_{-0.29} \pm 0.02$$
$$C = -0.52^{+0.22}_{-0.20} \pm 0.03$$
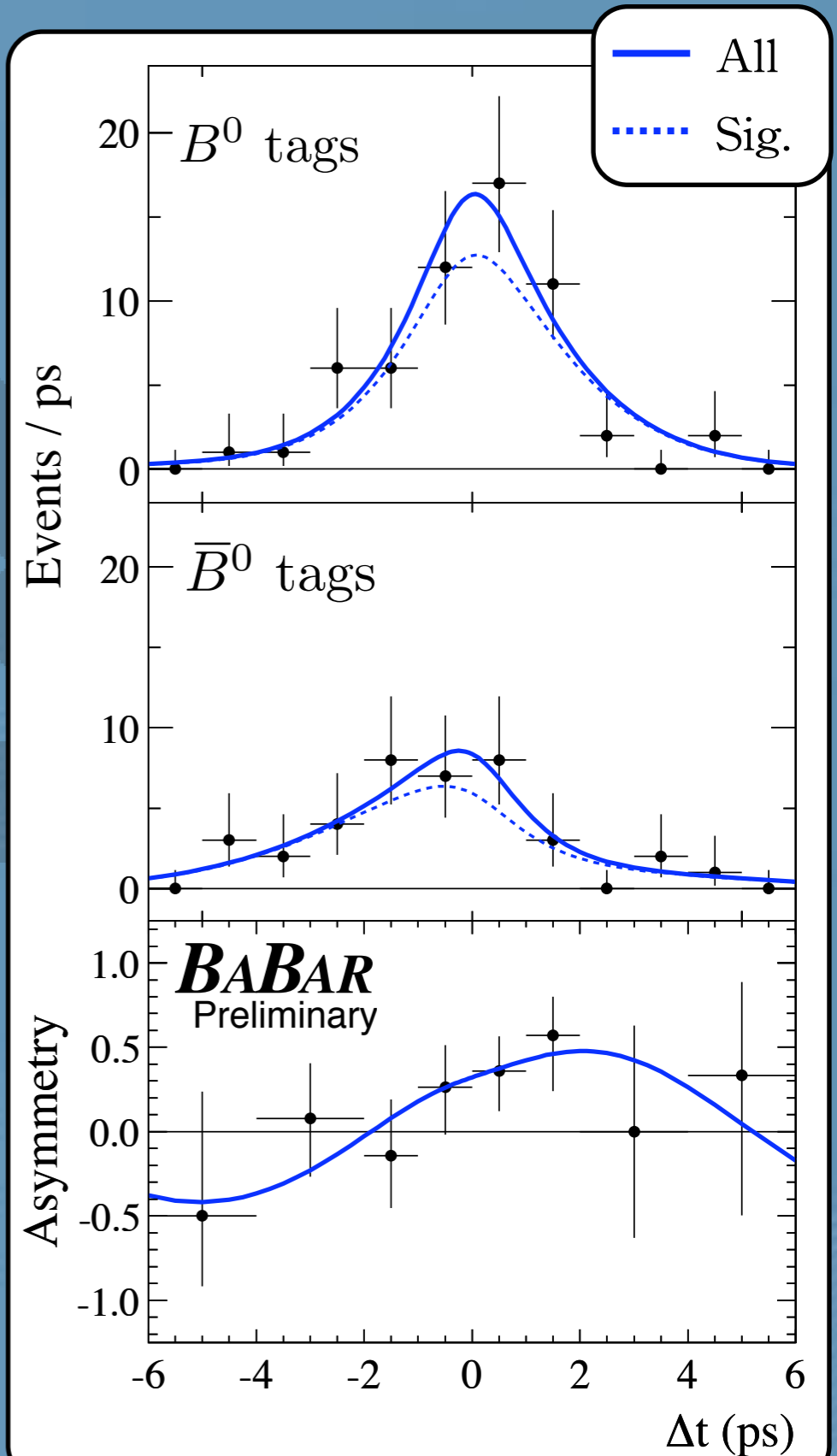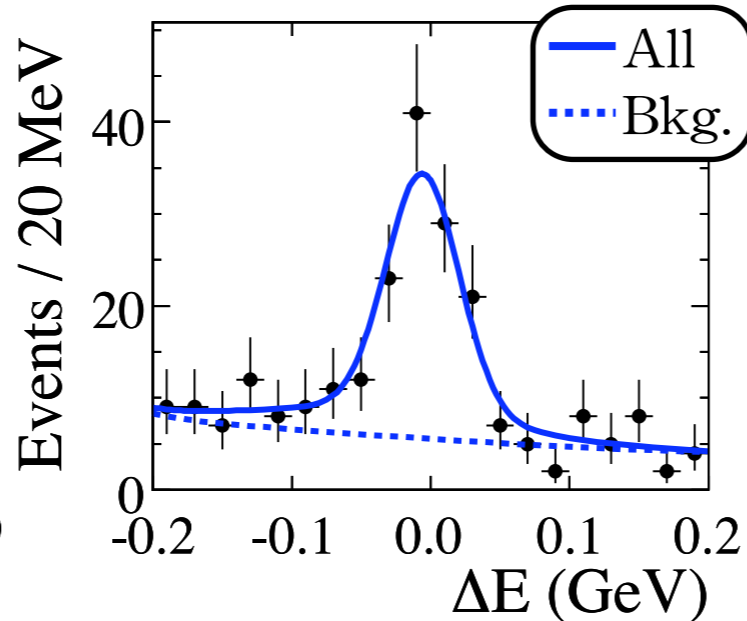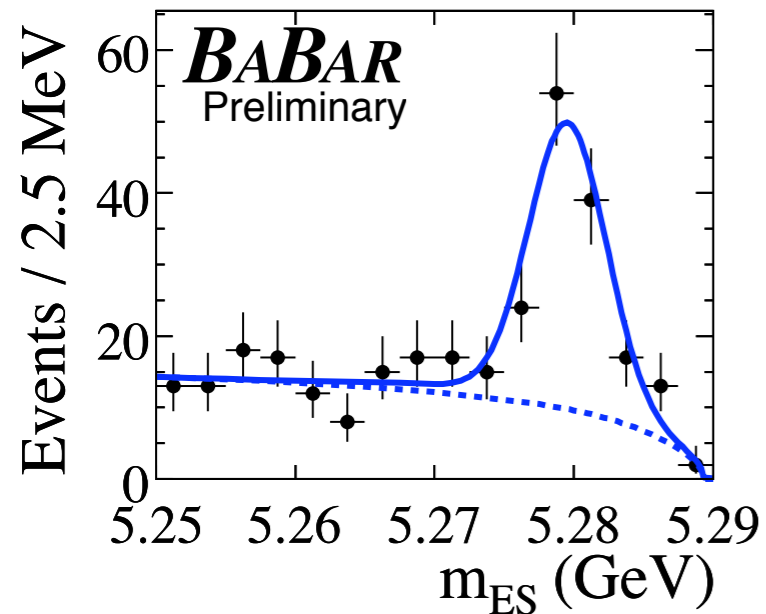
$B^0 \to K^+ K^- K_S^0$

arXiv:0808.0700

- Reconstruct $K_S^0 \to \pi^+\pi^-$ and $\pi^0\pi^0$.
- Time-dependent amplitude analysis, model uses $\phi K_S^0, f_0 K_S^0, X_0 K_S^0, \ NR, \ \chi_{c0} K_S^0, D^+ K^-, D_s^+ K^-$
- Fit entire Dalitz plot, then fit low-mass ($m_{K^+K^-} < 1.1$ GeV) and high-mass ($m_{K^+K^-} > 1.1$ GeV) regions.

Fit	Signal yield
Whole DP	1428 ± 47
High-Mass	1011 ± 39
Low-mass	421 ± 25

$\frac{\pi}{2} - \beta$ ambiguity in $\sin 2\beta$ ruled out at 4.8σ.

Fit	$A_{CP}\ (-C_f)$	$\beta_{\mathrm{eff}}\ (\beta_{\mathrm{SM}} \simeq 0.37)$
Whole DP	$0.03 \pm 0.07 \pm 0.02$	$0.44 \pm 0.07 \pm 0.02$
High-Mass	$0.05 \pm 0.09 \pm 0.04$	$0.52 \pm 0.08 \pm 0.03$
ϕK_S^0	$0.14 \pm 0.19 \pm 0.02$	$0.13 \pm 0.13 \pm 0.02$
$f_0 K_S^0$	$0.01 \pm 0.26 \pm 0.07$	$0.15 \pm 0.13 \pm 0.03$

$_s\mathcal{P}lots$ [1]

Accumulate probability to be signal (computed without plotted variable) in bins of variable of interest. Overlay normalized PDF.
[1]Pivk and LeDiberder, NIM Phys. Res., Sect. A 555, 356 (2005).

$B^0 \rightarrow \pi^0 K^0_S$
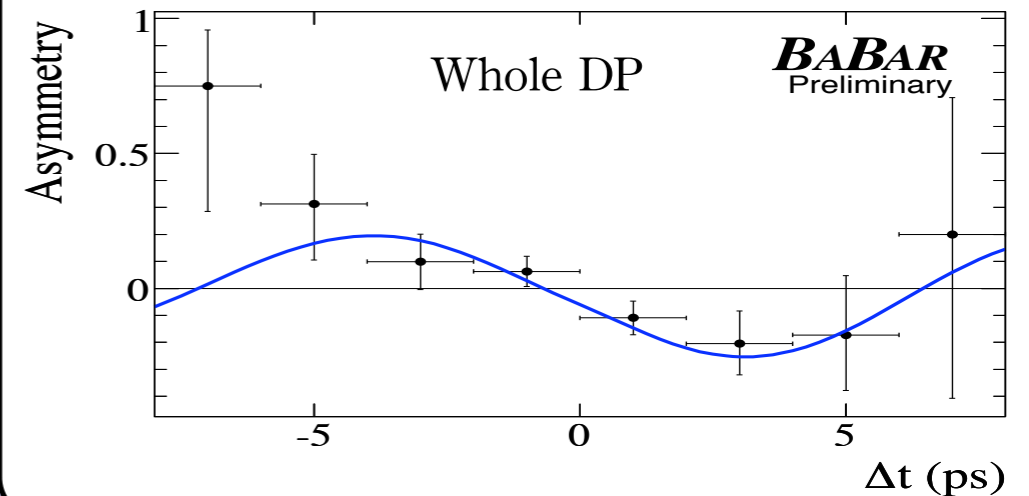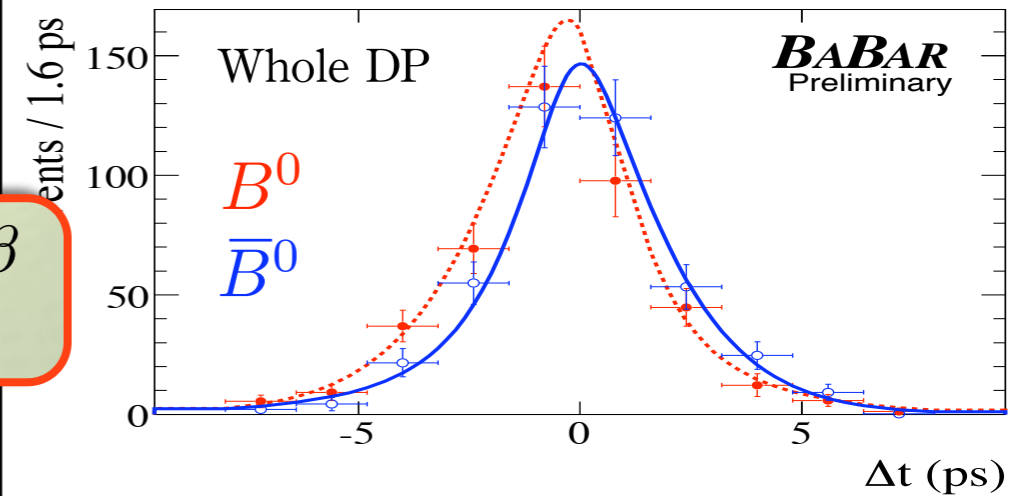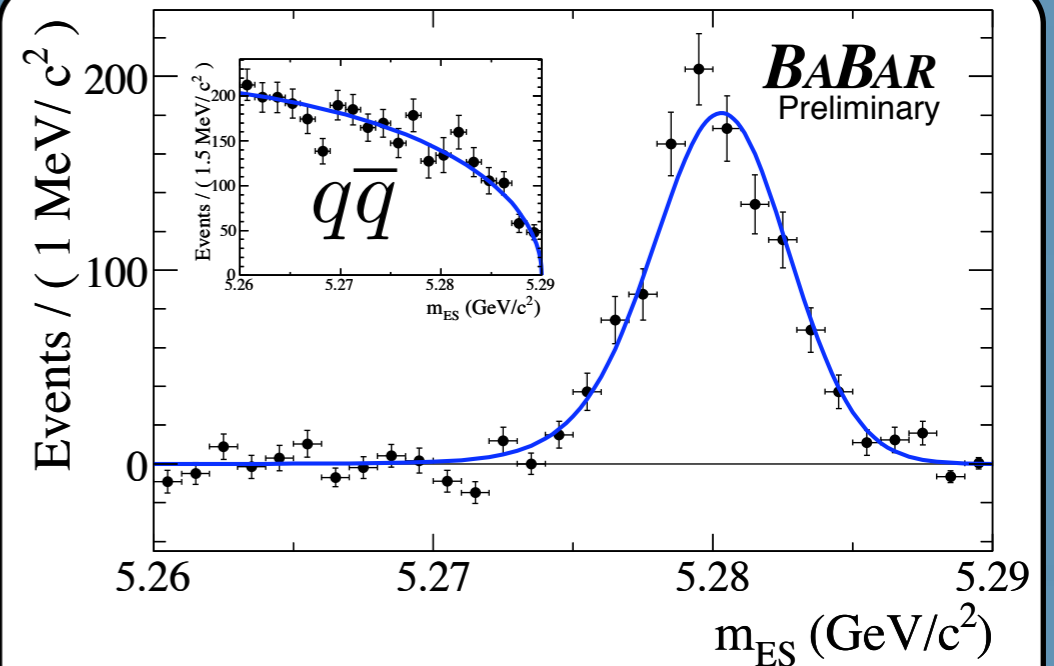
arXiv:0809.1174 (submitted to PRD)

- No tracks from B decay vertex!

- 60% of signal B candidates make hits in inner silicon tracker (SVT).

- Obtain Δt in these events w/ constraints on average interaction point and B lifetime.

- Δt resolution comparable to other modes (~1ps).

- All 556 ± 32 signal events constrain C.

B^0 tags

$\overline{B}^0$ tags

BABAR Preliminary

Events / ps

Asymmetry

Δt (ps)

Events/0.008

(a)

BABAR Preliminary

$m_{miss}(GeV/c^2)$

Events/0.03

$m_B(GeV/c^2)$
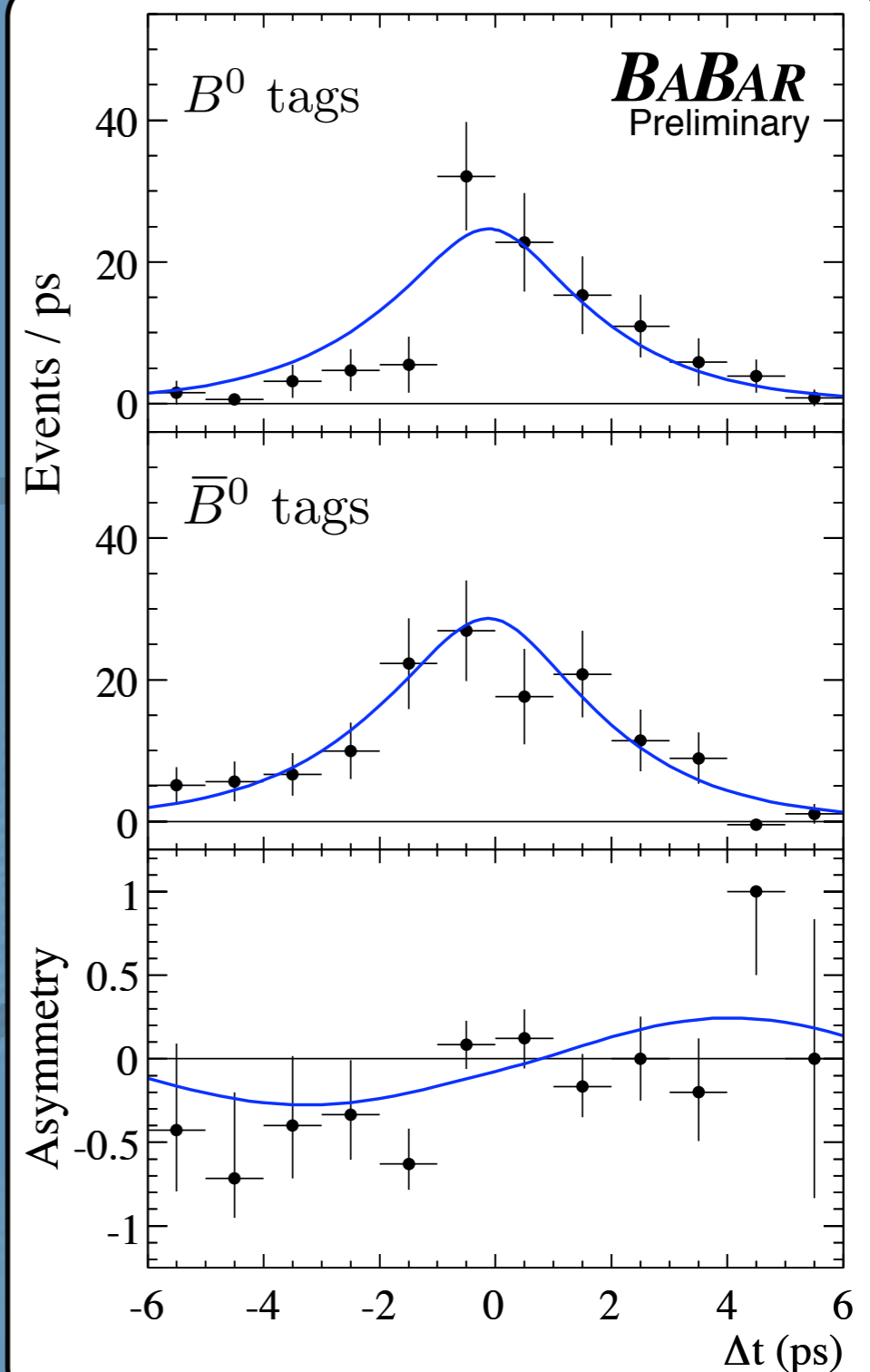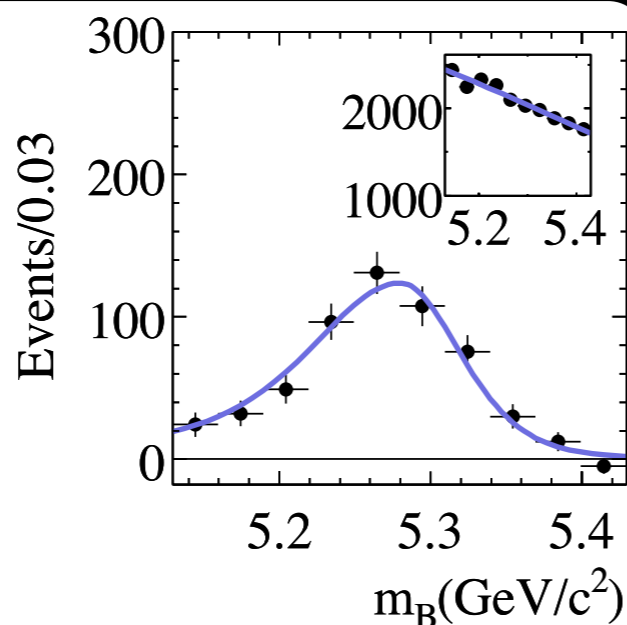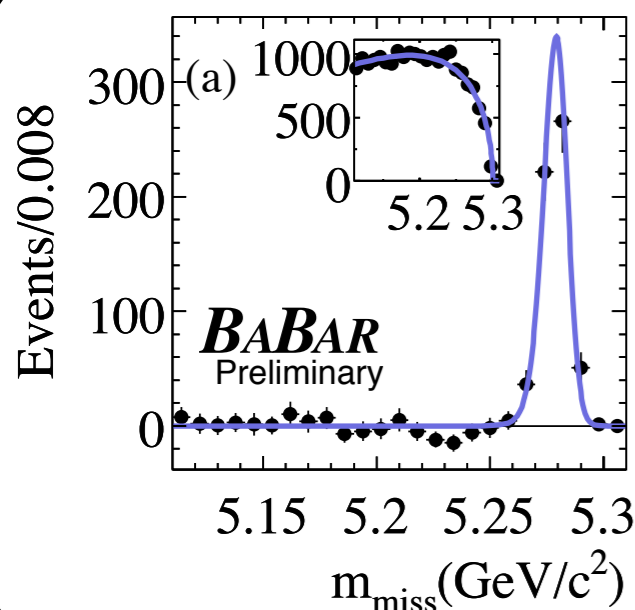
$$S = 0.55 \pm 0.20 \pm 0.03$$
$$C = 0.13 \pm 0.13 \pm 0.03$$

Results Summary

<table>
<tr><th></th><th>$-\eta_f S_f$</th><th>C_f</th></tr>
<tr><td>$\eta' K^0$</td><td>$0.55 \pm 0.08 \pm 0.02$</td><td>$-0.09 \pm 0.06 \pm 0.02$</td></tr>
<tr><td>$\eta' K_S^0$</td><td>$0.53 \pm 0.08 \pm 0.02$</td><td>$-0.11 \pm 0.06 \pm 0.02$</td></tr>
<tr><td>$\eta' K_L^0$</td><td>$0.64 \pm 0.20 \pm 0.03$</td><td>$0.05 \pm 0.15 \pm 0.03$</td></tr>
</table>

- In 2005, naive average of ΔS was 3.7σ from zero.
- Discrepancy has shrunk to 0.7σ.
- C measurements consistent w/ 0.
- No indication of new physics.

- The B-factories have exceeded all expectations!
- CKM phase is the dominant source of CP violation!

sin $2\beta_{\mathrm{eff}}$

HF AG
CKM2008
PRELIMINARY

b→ccs World Average 0.67 ± 0.02

ϕK^0
BaBar $0.26 \pm 0.26 \pm 0.03$
Belle $0.67 ^{+0.22}_{-0.32}$
Average $0.44 ^{+0.17}_{-0.18}$

$\eta' K^0$
BaBar $0.57 \pm 0.08 \pm 0.02$
Belle $0.64 \pm 0.10 \pm 0.04$
Average 0.59 ± 0.07

$K_S K_S K_S$
BaBar $0.90 ^{+0.18}_{-0.20} {}^{+0.03}_{-0.04}$
Belle $0.30 \pm 0.32 \pm 0.08$
Average 0.74 ± 0.17

$\pi^0 K^0$
BaBar $0.55 \pm 0.20 \pm 0.03$
Belle $0.67 \pm 0.31 \pm 0.08$
Average 0.57 ± 0.17

$\rho^0 K_S$
BaBar $0.61 ^{+0.22}_{-0.24} \pm 0.09 \pm 0.08$
Belle $0.64 ^{+0.19}_{-0.25} \pm 0.09 \pm 0.10$
Average $0.63 ^{+0.17}_{-0.21}$

ωK_S
BaBar $0.55 ^{+0.26}_{-0.29} \pm 0.02$
Belle $0.11 \pm 0.46 \pm 0.07$
Average 0.45 ± 0.24

$f_0 K_S$
BaBar $0.64 ^{+0.15}_{-0.18}$
Belle $0.60 ^{+0.16}_{-0.19}$
Average $0.62 ^{+0.11}_{-0.13}$

$K^+ K^- K^0$
BaBar $0.86 \pm 0.08 \pm 0.03$
Belle $0.68 \pm 0.15 \pm 0.03 ^{+0.21}_{-0.13}$
Average 0.82 ± 0.07

-0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6

New physics flavor puzzle at the LHC

- New physics (NP) expected at energy scale $\Lambda \sim 1$ TeV,
  - to prevent divergence of the Higgs mass.
- New physics flavor puzzle:

  > How does NP, expected to have generic flavor structure, maintain the observed flavor structure of the Standard Model?

- Solution: NP follows principle of minimal flavor violation[1] (MFV);
  - i.e., the SM Yukawa couplings are the dominant source of flavor violation.

- It may be possible to experimentally *exclude* MFV at the LHC; consider this fortunate scenario[2]:
  - $\tilde{t}$ is next-to-lightest SUSY particle.
  - $\tilde{t} \to \chi_1^0 b$ is kinematically forbidden.
  - Large decay rate for $\tilde{t} \to \chi_1^0 c$ can exclude MFV.

[1] D'Ambrosio, Giudice, Isidori, Strumia, hep-ph/0207036;
Cirigliano, Grinstein, Isidori, Wise, hep-ph/0507001, hep-ph/0608123;
Isidori, Mescia, Paradisi, Smith, Trine, hep-ph/0604074;
Nikolidakis, Smith, arXiv:0710.3129;

[2] Hiller and Nir, arXiv:0802.0916
Nir, arXiv:0708.1872

Summary

- $\sin 2\beta$ measured in $b \to c\bar{c}s$ decays such as $B^0 \to J/\psi K^0$.
- $\sin 2\beta_\mathrm{eff}$ measured in $b \to q\bar{q}s$ penguin decays such as $B^0 \to \eta' K^0$.
- In Standard Model $\sin 2\beta_\mathrm{eff} \simeq \sin 2\beta$.
- $\sin 2\beta_\mathrm{eff}$ sensitive to non-SM particles in the loop.

- In 2005, there was large discrepancy (~4σ) between $\sin 2\beta$ and $\sin 2\beta_\mathrm{eff}$.
- Current measurements differ by only ~1σ.
- CKM phase is the sole source of CP violation.

- New physics flavor puzzle:
  If new physics is there at $\Lambda \sim 1$ TeV, why do we find no evidence at B-factories?
- At LHC, Minimal Flavor Violation will be easier to exclude than confirm.
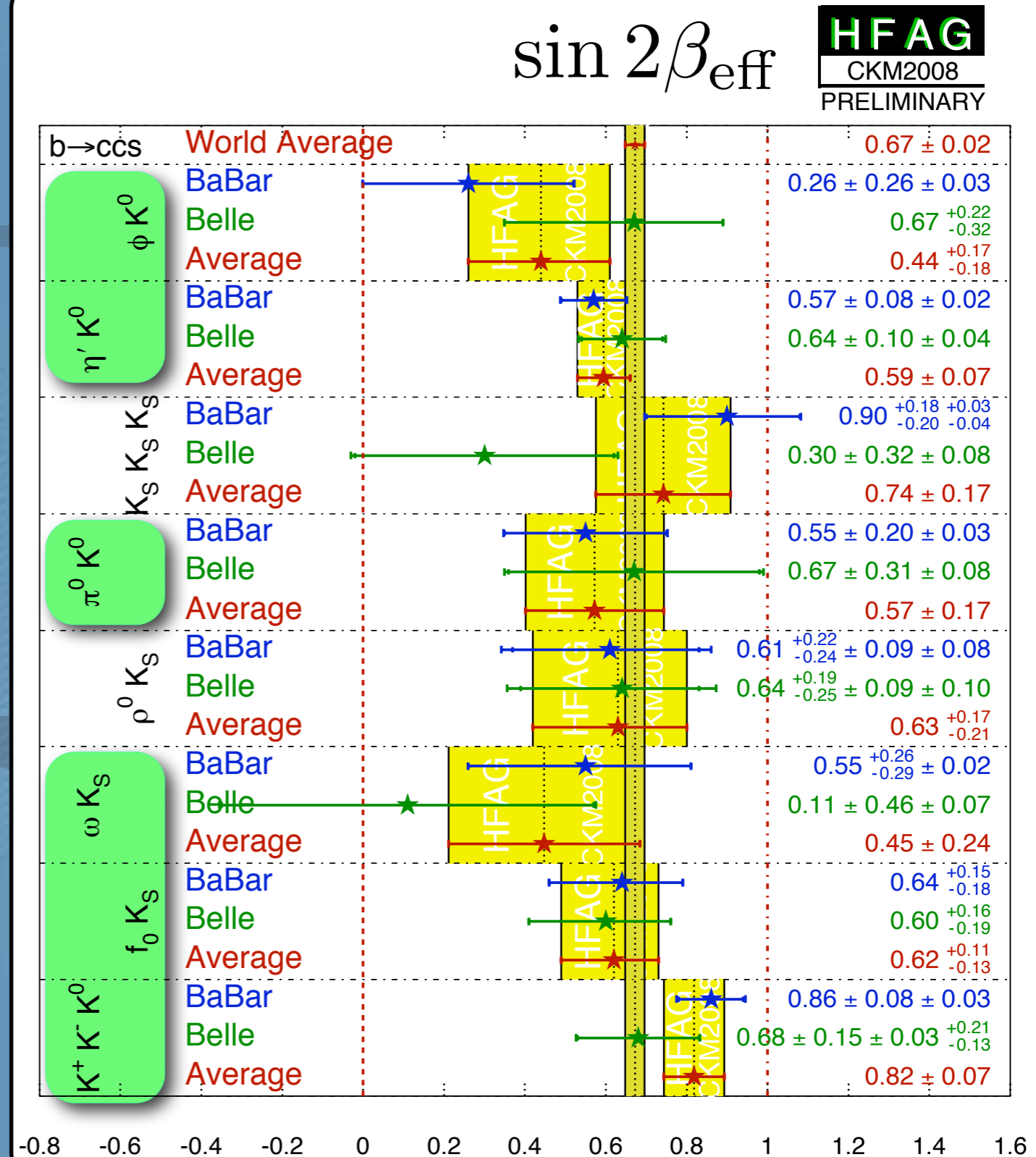
Extra slides

Summary

	$-\eta_f S_f$	C_f
$\eta' K^0$	$0.55 \pm 0.08 \pm 0.02$	$-0.09 \pm 0.06 \pm 0.02$
$\eta' K_S^0$	$0.53 \pm 0.08 \pm 0.02$	$-0.11 \pm 0.06 \pm 0.02$
$\eta' K_L^0$	$0.64 \pm 0.20 \pm 0.03$	$0.05 \pm 0.15 \pm 0.03$

$$C_f = -A_f$$

HFAG
CKM2008
PRELIMINARY

ϕK^0
BaBar $-0.14 \pm 0.19 \pm 0.02$
Belle $-0.31 \, ^{+0.21}_{-0.23} \pm 0.04 \pm 0.09$
Average -0.23 ± 0.15

$\eta' K^0$
BaBar $-0.08 \pm 0.06 \pm 0.02$
Belle $0.01 \pm 0.07 \pm 0.05$
Average -0.05 ± 0.05

$K_S K_S K_S$
BaBar $-0.16 \pm 0.17 \pm 0.03$
Belle $-0.31 \pm 0.20 \pm 0.07$
Average -0.23 ± 0.13

$\pi^0 K^0$
BaBar $0.13 \pm 0.13 \pm 0.03$
Belle $-0.14 \pm 0.13 \pm 0.06$
Average 0.01 ± 0.10

$\rho^0 K_S$
BaBar $0.02 \pm 0.27 \pm 0.08 \pm 0.06$
Belle $-0.03 \, ^{+0.24}_{-0.23} \pm 0.11 \pm 0.11$
Average -0.01 ± 0.20

ωK_S
BaBar $-0.52 \, ^{+0.22}_{-0.20} \pm 0.03$
Belle $0.09 \pm 0.29 \pm 0.06$
Average -0.32 ± 0.17

$f_0 K_S$
BaBar 0.16 ± 0.19
Belle 0.05 ± 0.18
Average 0.10 ± 0.13

$K^+ K^- K^0$
BaBar $-0.05 \pm 0.09 \pm 0.04$
Belle $0.09 \pm 0.10 \pm 0.05$
Average 0.01 ± 0.07

-1   -0.8   -0.6   -0.4   -0.2   0   0.2   0.4   0.6   0.8   1

44

A Tale of Two Bases

- The Standard Model describes Nature in terms of $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry.

- $SU(2)_L \times U(1)_Y$ sub-group is spontaneously broken by Higgs mechanism putting Yukawa term in Lagrangian:

$$\mathcal{L}_Y = -\lambda_{ij}^d \overline{Q}_i^L \phi d_j^R - \lambda_{ij}^u \overline{Q}_i^L \phi_c u_j^R + \text{h.c.},$$

- Change from flavor basis into new basis that diagonalizes $\lambda^{u,d}$:

$$\mathcal{L}_Y' = -\frac{v}{\sqrt{2}} \lambda_{ii}^{d\prime} \overline{d}_i^{L\prime} d_i^{R\prime} - \frac{v}{\sqrt{2}} \lambda_{ii}^{u\prime} \overline{u}_i^{L\prime} u_i^{R\prime} + \text{h.c.}$$

- This term describes quarks with masses:

$$m_{ii}^d = \frac{v}{\sqrt{2}} \lambda_{ii}^{d\prime}, \quad m_{ii}^u = \frac{v}{\sqrt{2}} \lambda_{ii}^{u\prime}$$

- Quark fields in this mass basis:

$$u_i^{L\prime} = U_{ij}^u u_i^L, \quad d_i^{L\prime} = U_{ij}^d d_i^L$$

$\lambda^{u,d}$	3x3 complex matrices
$\overline{Q}^L$	quark doublet
u^R, d^R	quark singlets
ϕ	Higgs doublet
i, j	flavor indices
$\phi_c \equiv -i\tau_2 \phi^*$	

$B\overline{B}$ Time Evolution

$$\Delta m_B \equiv m_H - m_L$$
$$\Delta\Gamma_B \equiv \Gamma_H - \Gamma_L$$

- Mass and flavor eigenstates differ:

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$
$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

- Note $\Delta\Gamma_B \ll \Delta m_B$ (in K system $\Delta\Gamma_K \simeq 2\Delta m_K$).

- Neutral B`s mix via second-order weak process (box diagram).

- Write time-dependent Schrodinger equation for two-state system with mixing and decay; write state of particle produced as B^0 at $t = 0$ in terms of mass states and eigenvalues of Hamiltonian $\lambda_{L,H}$:

$$|B^0_{\mathrm{phys}}(t)\rangle = \tfrac{1}{2p}\left[e^{-i\lambda_H t}|B_H\rangle + e^{-i\lambda_L t}|B_L\rangle\right]$$

- In terms of $M = (M_H + M_L)/2$ and $\Gamma \simeq \Gamma_H \simeq \Gamma_L$:

$$|B^0_{\mathrm{phys}}(t)\rangle = e^{-iMt}e^{-\Gamma t/2}\left[\cos\left(\tfrac{1}{2}\Delta m_B t\right)|B^0\rangle + i\tfrac{q}{p}\sin\left(\tfrac{1}{2}\Delta m_B t\right)|\overline{B}^0\rangle\right]$$

- Similarly for $|\overline{B}^0_{\mathrm{phys}}(t)\rangle$.
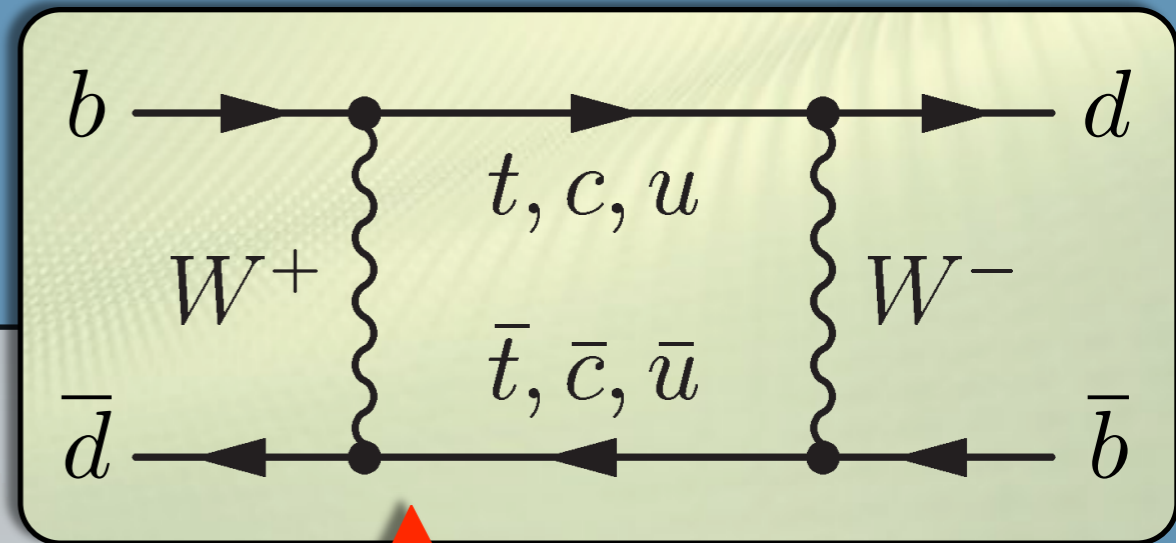
$\sin 2\beta_{\text{eff}}$ from $b \to q\bar{q}s$ penguin decays
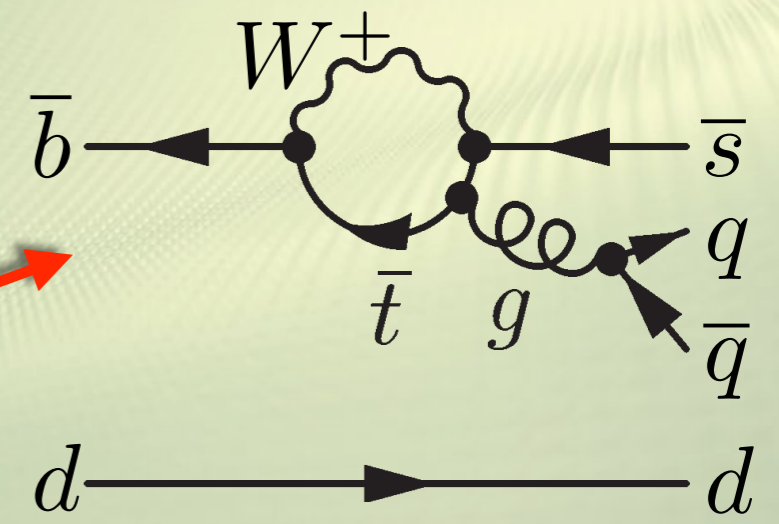
- $b \to q\bar{q}s$ decays occur via loop processes in SM.
- $b \to s$ penguins also sensitive to $\sin 2\beta$ but with theoretical uncertainty from tree and Cabibbo-suppressed penguin pollution:
- In terms of tree (T) and penguin (P_q, $q = u, c, t$) contributions:

$$A_{\eta' K^0} = P_t V_{tb} V_{ts}^* + P_c V_{cb} V_{cs}^* + (P_u + T) V_{ub} V_{us}^*$$

- Unitarity gives

$$A_{\eta' K^0} = (P_c - P_t) V_{cb} V_{cs}^* + (P_u - P_t + T) V_{ub} V_{us}^*$$
$$\simeq \mathcal{O}(\lambda^2) + \mathcal{O}(\lambda^4)$$

- The first term, with same weak phase as $b \to c\bar{c}s$ decays, dominates.
- However, $|\overline{A}_{\eta' K^0}|/|A_{\eta' K^0}| - 1 = \mathcal{O}(\lambda^2)$, so

$$S_{\eta' K^0} = \sin 2\beta_{\text{eff}} \simeq \sin 2\beta$$
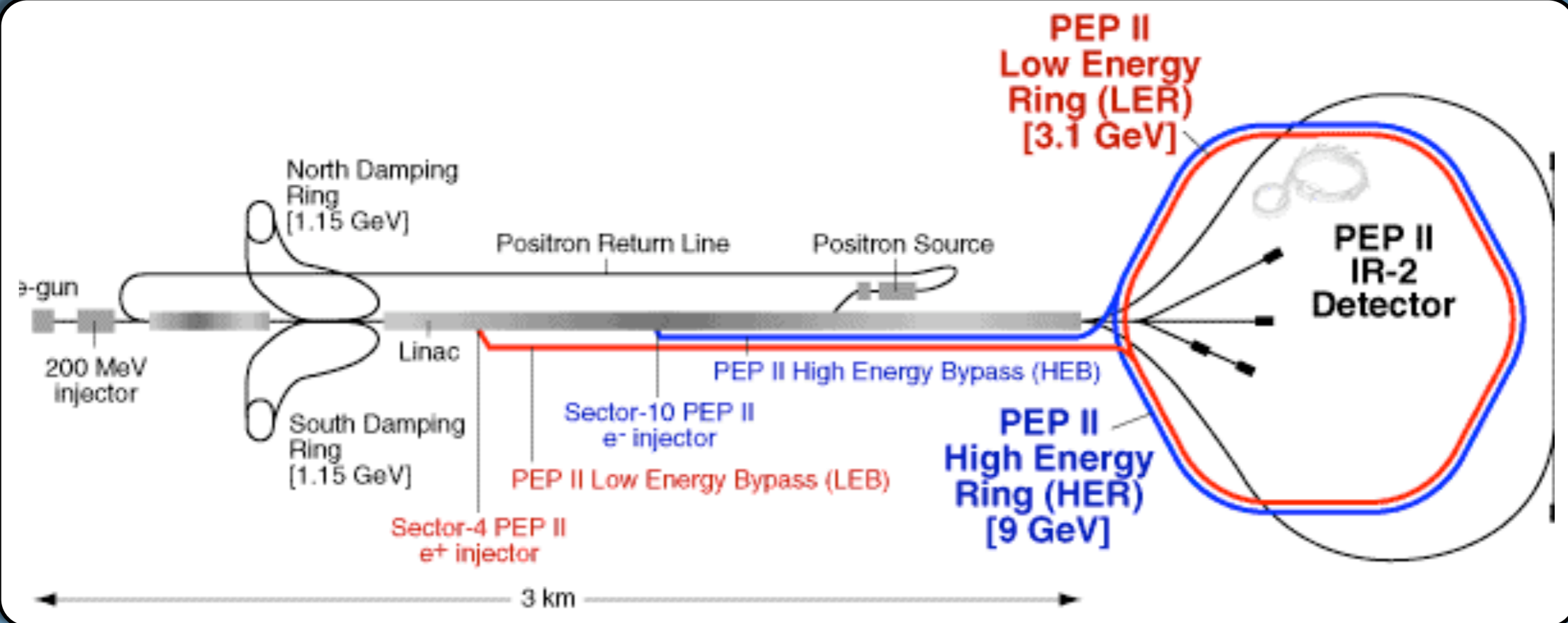
Maximum likelihood method

- Consider set of N measurements of a quantity x distributed according to a *probability density function* (PDF) $\mathcal{P}(x, \boldsymbol{\alpha})$ where $\boldsymbol{\alpha}$ is a set of n parameters $\boldsymbol{\alpha} = \{\alpha_1, \alpha_2, ..., \alpha_n\}$.

- The likelihood function is defined :
$$\mathcal{L} = \prod_i^N \mathcal{P}(x_i, \boldsymbol{\alpha})$$

- Given the data (x_i), the likelihood gives the relative probability for values of parameters $\boldsymbol{\alpha}$. The maximum of $\mathcal{L}$ over parameter space $\boldsymbol{\alpha}$ gives an unbiased estimate of $\boldsymbol{\alpha}$.

- For large N, $\mathcal{L}(\alpha_i)$ is Gaussian near maximum $\mathcal{L}_{\max} \equiv \mathcal{L}(\hat{\alpha}_i)$:

$$\mathcal{L}(\alpha_i) = \mathcal{L}_{\max} e^{-\frac{(\alpha_i - \hat{\alpha}_i)^2}{2\sigma^2}}$$

- Statistical uncertainty σ_i on α_i is $\frac{1}{\sigma_i^2} = \frac{\partial^2 \ln \mathcal{L}}{\partial \alpha_i^2}$.

- We compute the significance $(\mathcal{S})$ of a fit result $(\mathcal{L}_{\max})$ relative to some other hypothesis, e.g. the zero signal hypothesis $(\mathcal{L}_0)$, with the likelihood ratio test: $\mathcal{S} = -2 \ln \frac{\mathcal{L}_{\max}}{\mathcal{L}_0}$.

ML fit specifics

- If N is a random variable, construct *extended* likelihood with factor for Poisson probability of making N measurements when expecting ν.

- We use multiple observables so $x \to \mathbf{x}$, where $\mathbf{x} = \{x_1, x_2, ..., x_m\}$.

- The PDF $\mathcal{P}(\mathbf{x}, \boldsymbol{\alpha})$ is a composite with each part corresponding to a component of the data, such as signal or background.

- Correlations between variables of $\mathbf{x}$ are low (<5%), so we factorize the PDF for each fit component j: $\quad \mathcal{P}_j(\mathbf{x}) = \mathcal{P}_j(x_1)\mathcal{P}_j(x_2)...\mathcal{P}_j(x_m)$.

- In practice, $\mathcal{L}$ is very small and computationally difficult, so we minimize $-2\ln\mathcal{L}$ instead of maximizing $\mathcal{L}$.

- The likelihood for N events with signal (sig) and background (bkg) components:

$$\mathcal{L} = \frac{e^{-(\nu_{\mathrm{sig}}+\nu_{\mathrm{bkg}})}}{N!} \prod_i^N \nu_{\mathrm{sig}}\mathcal{P}_{\mathrm{sig}}(\mathbf{x}_i, \boldsymbol{\alpha}_{\mathrm{sig}}) + \nu_{\mathrm{bkg}}\mathcal{P}_{\mathrm{bkg}}(\mathbf{x}_i, \boldsymbol{\alpha}_{\mathrm{bkg}})$$

where ν_{sig} and ν_{bkg} (the estimators of the sig and bkg event yields) are free to vary in the fit.

KL cut optimization

Table A.1: Results from cut optimization study for $\eta'_{\eta\pi\pi} K^0_L$. The "Very Tight" cut values maximize signal significance $(S/\sqrt{S+B})$. The "Loose" cut values minimize the errors on S and C from toy MC studies and are used in this analysis. We report cut values, events entering the Run1-6 fit, signal efficiency, expected Run1-6 signal yield, mean of the S and C error distributions for embedded toys with Run1-6 statistics, and blind fit values to run1-6 data as a final crosscheck.

	Very Tight	Tight	Loose	Very Loose
NN output Cut	0.50	0.40	0.30	0.20
$P_{\mathrm{miss}}^{\mathrm{proj}}$ Cut	-0.46	-0.60	-0.70	-0.80
$\cos\theta_{P_{\mathrm{miss}}}$ Cut	0.93	0.94	0.95	0.96
Events to Fit	6253	8826	12085	14992
MC ϵ (%)	15.2	17.6	19.8	21.0
Expected nSig	249	310	353	375
S error	0.310 ± 0.004	0.273 ± 0.003	0.257 ± 0.003	0.262 ± 0.003
C error	0.222 ± 0.002	0.198 ± 0.002	0.191 ± 0.002	0.190 ± 0.001
blind S	-0.76 ± 0.26	-0.68 ± 0.24	-0.68 ± 0.22	-0.59 ± 0.22
blind C	0.09 ± 0.22	0.05 ± 0.21	0.04 ± 0.19	0.05 ± 0.19

Charm $B\bar{B}$ background

charmless sPlot

$m_{\rm ES}$ (GeV)

- Typically, charm events are absorbed into continuum background yield in ML fit.
- In previous analyses, charmless yield floated 1.6 -- 5 times higher than expected.
- Bias on charmless yield was negative.
- In mode etap K+, projection of charmless events onto mES shows contamination from non-peaking events -- charm or qq?
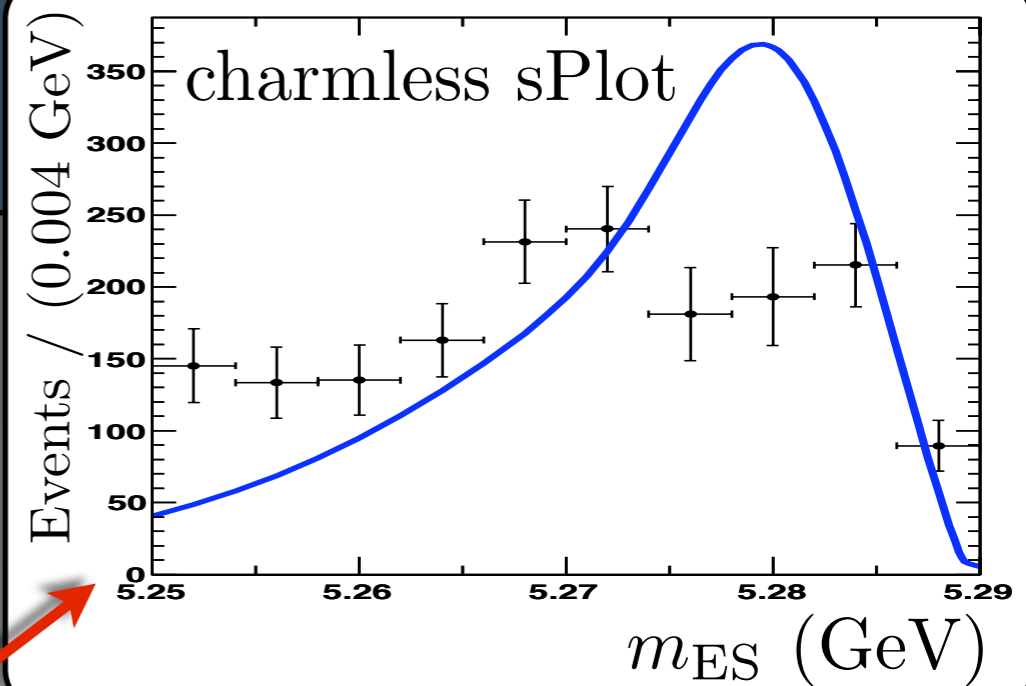
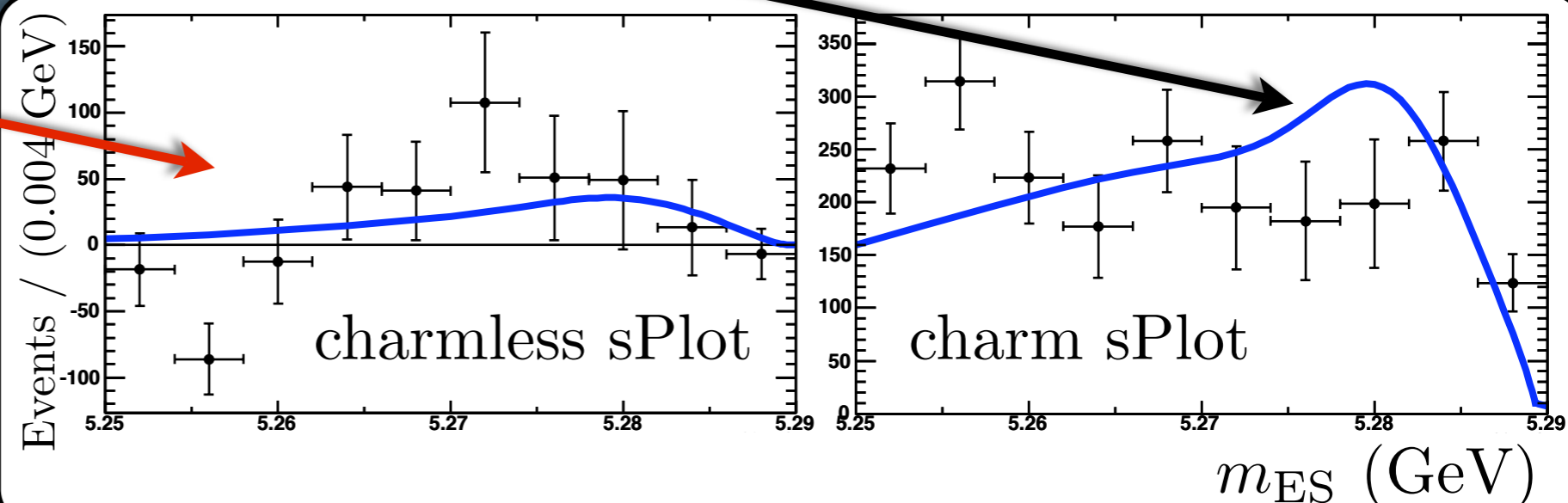## sPlots

Accumulate probability to be signal (computed without plotted variable) in bins of variable of interest. Overlay normalized PDF.

Charm PDF is $q\bar{q}$-like with small peaking component.

- With charm component in ML fit projections look more reasonable.
- Charm and charmless yields float to reasonable values in ML fit.

charmless sPlot

charm sPlot

$m_{\rm ES}$ (GeV)

Tagging algorithm

Semileptonic B decay

- Neural-network-based algorithm assigns each B_{tag} candidate to 1 of 6 categories.

- Category is determined by continuous output of algorithm (and lepton in the B_{tag} final state).

- Cleanest tagging from semileptonic decays, such as $B^0 \to D^{*-} l^+ \nu_l$.

- Clean tagging from $b \to c \to s$ decays, such as $B^0 \to D^{*-} \rho^+$, $D^{*-} \to \overline{D}{}^0 \pi^-$, $\overline{D}{}^0 \to K^+ \pi^-$
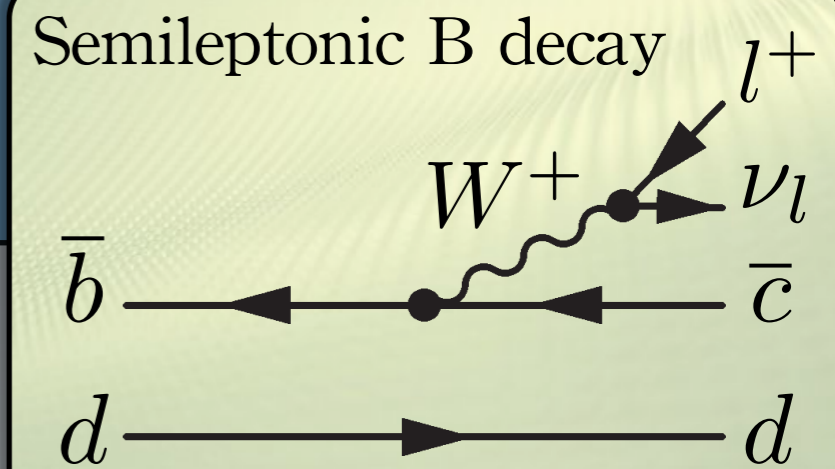
Δt resolution function

- Sum of 3 Gaussians (*core, tail,* and *outlier*).

- The means and widths of core, tail Gaussians are scaled by uncertainty on Δt ($\sigma_{\Delta t}$).

$$\mathcal{R}(\Delta t, \sigma_{\Delta t}) = (1 - f_{\text{tail}} - f_{\text{out}})G(\Delta t, \mu_{\text{core}}\sigma_{\Delta t}, \sigma_{\text{core}}\sigma_{\Delta t})$$
$$+ f_{\text{tail}}G(\Delta t, \mu_{\text{tail}}\sigma_{\Delta t}, \sigma_{\text{tail}}\sigma_{\Delta t}) + f_{\text{out}}G(\Delta t, \mu_{\text{out}}, \sigma_{\text{out}})$$

$G(x, \mu, \sigma)$ is Gaussian in x of mean μ and width σ.

- Parameters differ b/w tagging categories.
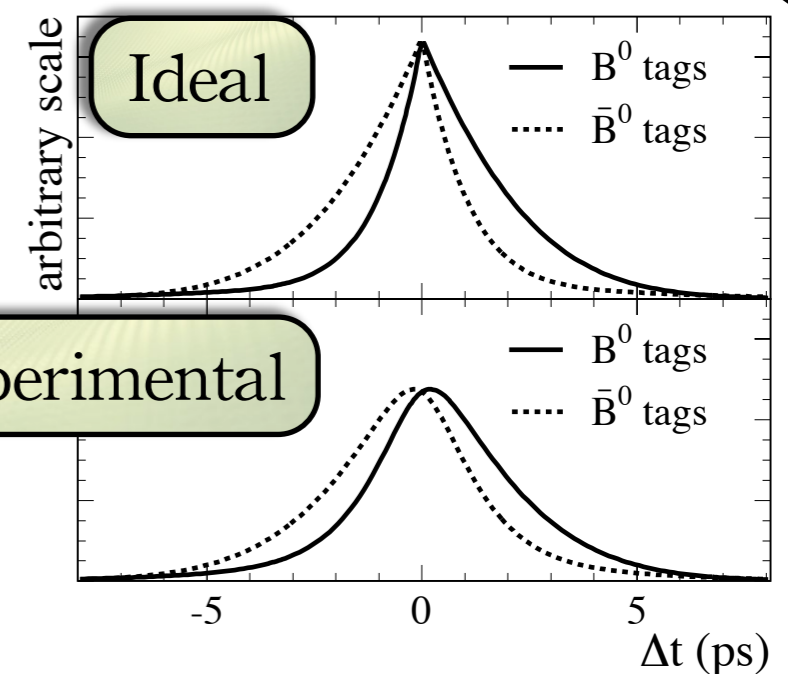
Validating fit uncertainties

Table 1: Mean values of the error distributions for S and C and the RMS of the S and C distributions for each sub-mode from 140-550 embedded toy MC experiments. (The number of experiments is the maximum without oversampling the signal MC.) We also report the averaged sub-mode results and the results from 175 toy experiments for the simultaneous fit. All results are reported in units of 10^{-3}.

Final state	Mean of S Error	RMS of S Error	RMS of S dist.	Mean of C Error	RMS of C Error	RMS of C dist.
$\eta'_{\eta\pi\pi}K^0_S$	156 ± 1	14 ± 1	167 ± 8	115 ± 1	5 ± 1	121 ± 6
$\eta'_{\rho\gamma}K^0_S$	112 ± 1	8 ± 1	114 ± 7	88 ± 1	3 ± 1	97 ± 6
$\eta'_{\eta\pi\pi}K^0_{S00}$	381 ± 5	75 ± 5	481 ± 34	267 ± 2	31 ± 2	280 ± 20
$\eta'_{\rho\gamma}K^0_{S00}$	325 ± 3	53 ± 3	357 ± 22	258 ± 2	36 ± 2	267 ± 16
$\eta'_{5\pi}K^0_S$	246 ± 3	38 ± 3	280 ± 20	180 ± 1	14 ± 1	192 ± 14
$\eta'_{\eta\pi\pi}K^0_L$	271 ± 2	32 ± 2	278 ± 18	199 ± 1	15 ± 1	201 ± 13
$\eta'_{5\pi}K^0_L$	358 ± 6	70 ± 6	416 ± 35	265 ± 3	32 ± 3	263 ± 22
Weighted Average :	76 ± 0	7 ± 0	79 ± 5	57 ± 0	2 ± 0	61 ± 4
Simultaneous Fit:	75 ± 0	3 ± 0	75 ± 6	58 ± 0	2 ± 0	61 ± 6

Systematic Errors

Source of error	$\sigma(S)$	$\sigma(C)$
Beam position/size	0.002	0.001
SVT alignment	+0.002 −0.001	+0.003 −0.002
Tag-side interference	0.001	0.015
Self-crossfeed	0.006	0.003
Fit Bias	0.006	0.006
PDF Shapes	0.005	0.009
$B\bar{B}$ Background	0.008	0.004
Signal Δt Shape	0.009	0.010
Total	0.016	0.022

- **Beamspot position**: Fit MC with reasonable variations in y, sig y.

- **SVT alignment**: Fit MC with reasonable SVT mis-alignment.

- **Tag-side interference**: With toy MC estimate effect of interference b/w CKM-suppressed bb ra ub c db and favored b ra u cb d amplitudes

- **Misreconstructed Signal**: Depending on sub-mode, in 1-4% of reconstructed signal events we swap track with rest of event. We embed various concentrations of *self-crossfeed* to estimate effect on DT and S/C.

- **Fit bias**: Take uncertainty on fit bias as systematic.

- **PDF parameterization**: Vary fixed params by amounts found in studies of data control samples (Bflav, B ra D pi, eta` K+) take DS/DC as systematic.

- **BB background**: Vary CP params for chls, chrm components; vary fixed charmless yield by +-20%.

- **Signal DT parameterization** : By comparing toy MC studies performed with DT params (calR and tagging) from signal and Bflav MC, we estimate effects due to differences between signal and Bflav data.

Crosschecks

- Including PDFs for m_η, m_ρ, θ^ρ_{dec} does not improve precision on S and C.

- Fit is stable without PDFs for (one-at-a-time). m_{ES}, ΔE, and $\mathcal{F}$

- S and C are consistent across tagging categories.

- Δt model is reasonable: $\tau = 1.53 \pm 0.07$ (PDG is 1.5 ± 0.01)

- S and C in charged modes consistent with zero.

Tag Cat	S	C
Lepton	-0.670 ± 0.134	0.122 ± 0.105
Kaon1	-0.315 ± 0.146	0.132 ± 0.107
Kaon2	-0.569 ± 0.150	0.297 ± 0.117
KaonPion	-0.246 ± 0.255	0.080 ± 0.185
Pions	-0.205 ± 0.365	0.263 ± 0.257
Other	-1.414 ± 1.010	0.624 ± 0.710
Weighted Average	-0.492 ± 0.076	0.174 ± 0.057
Nominal Result	-0.481 ± 0.078	0.174 ± 0.058

Fit vars	$m_{\text{ES}}, \Delta E, \mathcal{F}, \Delta t$	$\Delta E, \mathcal{F}, \Delta t$	$m_{\text{ES}}, \mathcal{F}, \Delta t$	$m_{\text{ES}}, \Delta E, \Delta t$
S	-0.481 ± 0.078	-0.471 ± 0.080	-0.512 ± 0.077	-0.535 ± 0.082
C	0.174 ± 0.058	0.159 ± 0.062	0.164 ± 0.059	0.165 ± 0.063
Signal Yields				
$\eta'_{\eta\pi\pi} K^0_S$	468.8 ± 23.5	465.4 ± 26.2	461.8 ± 23.5	475.1 ± 24.9
$\eta'_{\rho\gamma} K^0_S$	999.0 ± 39.6	997.0 ± 47.5	966.7 ± 46.9	1007.2 ± 45.4
$\eta'_{\eta\pi\pi} K^0_{S00}$	104.3 ± 13.0	107.4 ± 15.8	104.3 ± 12.7	111.3 ± 18.0
$\eta'_{\rho\gamma} K^0_{S00}$	201.9 ± 27.4	288.7 ± 44.6	196.2 ± 29.7	201.9 ± 44.9
$\eta'_{5\pi} K^0_S$	170.5 ± 14.1	177.4 ± 15.8	175.9 ± 23.1	172.3 ± 14.9
$\eta'_{\eta\pi\pi} K^0_L$	331.5 ± 31.4	334.9 ± 31.5	334.6 ± 29.1	334.6 ± 31.5
$\eta'_{5\pi} K^0_L$	163.9 ± 21.8	160.9 ± 21.6	160.8 ± 19.8	160.7 ± 21.6

	Nominal Fit	All-Variable Fit
$\eta'_{\eta\pi\pi} K^0_S$		
S	-0.622 ± 0.166	-0.629 ± 0.165
C	0.231 ± 0.110	0.217 ± 0.109
$\eta'_{\rho\gamma} K^0_S$		
S	-0.370 ± 0.117	-0.373 ± 0.116
C	0.217 ± 0.090	0.199 ± 0.086
$\eta'_{\eta\pi\pi} K^0_{S00}$		
S	-0.402 ± 0.347	-0.390 ± 0.342
C	0.232 ± 0.301	0.266 ± 0.301
$\eta'_{\rho\gamma} K^0_{S00}$		
S	-0.179 ± 0.331	-0.518 ± 0.336
C	0.029 ± 0.261	0.107 ± 0.263
$\eta'_{5\pi} K^0_S$		
S	-0.650 ± 0.261	-0.671 ± 0.260
C	0.036 ± 0.199	0.039 ± 0.198
$\eta'_{\eta\pi\pi} K^0_L$		
S	-0.684 ± 0.223	-0.692 ± 0.218
C	0.036 ± 0.194	0.033 ± 0.184
combined S	-0.482 ± 0.079	-0.507 ± 0.078
combined C	0.179 ± 0.059	0.171 ± 0.058

Averaging results
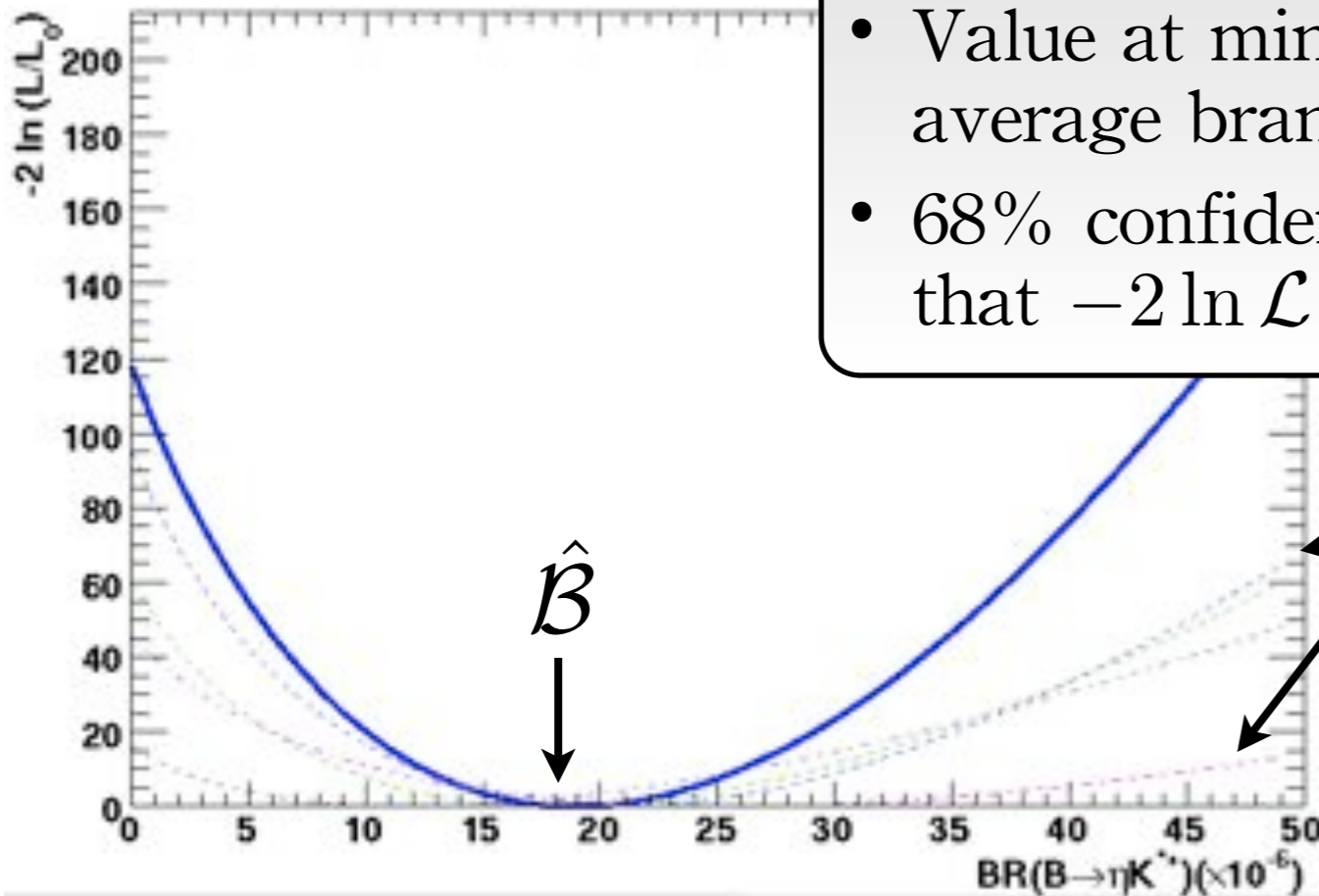
- In LMR:
- Obtain $-2\ln\mathcal{L}_f$ as function of ηK_1^* branching fraction ($\mathcal{B}$) for each sub-mode.
- Convolve $-2\ln\mathcal{L}_f(\mathcal{B})$ w/ Gaussian of with σ_{syst}.
- Value at minimum of $\sum -2\ln\mathcal{L}_f(\mathcal{B})$ is average branching fraction ($\hat{\mathcal{B}}$).
- 68% confidence interval on $\hat{\mathcal{B}}$ is σ such that $-2\ln\mathcal{L}(\hat{\mathcal{B}}\pm\sigma)=1$.

Dashed sub-mode curves

- In HMR:
  - ηK_0^* and ηK_2^* are highly correlated (40%).
  - Combining with $-2\ln\mathcal{L}_f(\mathcal{B})$ curves neglects correlations.
  - We average with simultaneous fits (as in $\eta'K^0$ analysis), one fit for 2 neutral modes, one for 4 charged modes.